NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

ASSESSING THE RESILIENCE OF GLOBAL SEA ROUTES

by

Oscar R. Garcia Olalla

June 2012

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REPORT DOCUMENTATION PAGE			*Form Approved OMB No. 0704-0188*
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington DC 20503.			
1. AGENCY USE ONLY ***(Leave blank)***	**2. REPORT DATE** June 2012	**3. REPORT TYPE AND DATES COVERED** Master's Thesis	
4. TITLE AND SUBTITLE Assessing the Resilience of Global Sea Routes			**5. FUNDING NUMBERS**
6. AUTHOR(S) Oscar R. Garcia Olalla			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000			**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A			**10. SPONSORING/MONITORING AGENCY REPORT NUMBER**
11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government. IRB Protocol number ______N/A______.			
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited			**12b. DISTRIBUTION CODE** A

13. ABSTRACT (maximum 200 words)

This research develops an attacker-defender model of maritime trading. The defender's problem is represented as a minimum cost, multi-commodity network flow model. System cost is measured in terms of total ton-n.m. in the network. Our network contains the 120 most important ports in the world (by volume of cargo), 35 waypoints at sea, and 416 arcs. Port supply and demand have been estimated from different sources. Interdictions represent manmade disruption of the seaways, such as those in the presence of piracy. An interdicted arc is assumed to incur a penalty equivalent to the additional distance that a ship would need to travel in order to avoid the threat, or a total blockade of the arc in the case of straits and canals. We analyze several scenarios with varying assumptions on the defended arcs and the number of simultaneous interdictions. The most disruptive, single interdiction occurs in the Strait of Gibraltar, increasing cost by almost 25%, followed by the Straits of Bab el Mandeb (20%) and Suez Canal (19%). For two simultaneous interdictions, cost increases to 33%, but decreases to 23%, 8% and 1.5% when we defend three, four or five select straits and canals, respectively.

14. SUBJECT TERMS Maritime transport; Sea routes; Piracy; Network optimization model; Attacker-defender model			**15. NUMBER OF PAGES** 103
			16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT Unclassified	**18. SECURITY CLASSIFICATION OF THIS PAGE** Unclassified	**19. SECURITY CLASSIFICATION OF ABSTRACT** Unclassified	**20. LIMITATION OF ABSTRACT** UU

NSN 7540-01-280-5500 Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18

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ASSESSING THE RESILIENCE OF GLOBAL SEA ROUTES

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Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN OPERATIONS RESEARCH

from the

NAVAL POSTGRADUATE SCHOOL
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ABSTRACT

This research develops an attacker-defender model of maritime trading. The defender's problem is represented as a minimum cost, multi-commodity network flow model. System cost is measured in terms of total ton-nautical miles in the network. Our network contains the 120 most important ports in the world (by volume of cargo), 35 waypoints at sea, and 416 arcs. Port supply and demand have been estimated from different sources. Interdictions represent manmade disruption of the seaways, such as those in the presence of piracy. An interdicted arc is assumed to incur a penalty equivalent to the additional distance that a ship would need to travel in order to avoid the threat, or a total blockade of the arc in the case of straits and canals. We analyze several scenarios with varying assumptions on the defended arcs and the number of simultaneous interdictions. The most disruptive, single interdiction occurs in the Strait of Gibraltar, increasing cost by almost 25%, followed by the Straits of Bab el Mandeb (20%) and Suez Canal (19%). For two simultaneous interdictions, cost increases to 33%, but decreases to 23%, 8% and 1.5% when we defend three, four or five select straits and canals, respectively.

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LIST OF ACRONYMS AND ABBREVIATIONS

AAPA	Association of Ports Authorities
AD	Attacker-Defender
CIA	Central Intelligence Agency
MIP	Mixed-Integer Program
n.m.	Nautical mile
TSI	Transportation Security Incident

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EXECUTIVE SUMMARY

Maritime transportation supports approximately 80% of total world trade; as such, the study of the vulnerability of containerized and bulk shipping to acts of piracy and terrorism is important for the global economy. During 2011, there were 45 vessels hijacked, 176 boarded, 113 fired upon and 105 reports of attempted attacks. Most of these attacks took place in the Gulf of Aden, crossed by some of the busiest routes in the world. 237 of these attacks were mounted by Somali pirates. This research assesses worst-case scenarios of disruption to maritime trade caused by piracy, small terrorist groups, or political reasons.

We develop and implement an attacker-defender, multi-commodity network optimization model in order to assess the resiliency of the world's maritime network to the interdiction of strategic maritime seaways. Specifically, our model determines optimal sets of one, two and three interdictions that would cause the largest cost (measured in ton-nautical miles) for the flow of cargo to meet all the demands.

Our network contains 120 nodes representing the most important ports in the world (based on volume of cargo), 35 waypoint nodes at sea, and 416 arcs. The supply and demand data to populate the model have been estimated from different sources, including: total volumes handled by each port, trade balances, import and export rates among countries, and a gravity model.

We assume the interdiction of an arc incurs a penalty equivalent to the additional distance that a ship would need to travel in order to avoid the threat. In cases of straits and canals we assume a total blockade of the arc, forcing the model to seek alternative routes of transportation.

We analyze several scenarios in which we manually set a limited number of defended arcs, vary the number of simultaneous interdictions allowed for the attacker, and enumerate a ranking of worst-case interdictions by cost.

Excluding cases where ports become isolated, we find that the attack (and closure) of the Strait of Gibraltar alone generates the largest disruption, with a cost

increase of 24.65% with respect to the non-interdicted network. We identify other important, single attacks in the Strait of Bab el Mandeb (cost increment of 19.79%), Suez Canal (18.70%), Panama Canal (7.66%), and Strait of Malacca (5.96%). In some of these cases, the interdiction is explained by the increase in distance the cargo would need to travel, whereas in other cases the predominant factor is the amount of cargo involved.

For two simultaneous interdictions, the interdiction of the Panama Canal and the Strait of Gibraltar generates the largest disruption, producing a cost increment of 33.22%. When the Panama and Suez canals, and the Strait of Gibraltar are assumed to be defended, the optimal interdictions become the Strait of Bab el Mandeb and the Strait of Malacca, with a cost increment of 22.54%.

Assuming all the arcs in Gibraltar, Panama, Suez and Bab el Mandeb are defended, the optimal simultaneous attack on two arcs involves the arcs of the straits of Malacca and Sunda, with 8.27% cost increase. If we allow three interdictions, an attack on the arcs in the straits of Malacca, Sunda and Lombok increases cost by 15.54%. When the Strait of Malacca is also defended, the cost of two interdictions decreases to 1.5%, and the cost of three interdictions decreases to 2.17%.

ACKNOWLEDGMENTS

I want to express my gratitude to Professor Javier Salmeron for his exceptional guidance, patience, and professionalism in directing this thesis.

I also would like to express my deep appreciation and gratitude to Distinguished Professor Gerald Brown. Thank you for your confidence and support.

To Captain Jeffrey Kline USN, for your knowledge and guidance in maritime operations.

Most importantly, I want to thank to my wife, Raquel, and my children, Alan, Piedad and Ian, for your support and understanding. You all are my source of energy and the only motive of all my effort.

Finally, I would like to thank the Argentine Air Force for giving me the opportunity to improve my knowledge to better serve my country.

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I. INTRODUCTION

A. PURPOSE OF THE STUDY

Maritime transportation supports approximately 80% of total world trade, and the U.S. deems maritime security of "vital national interest" (Department of Homeland Security, 2005). Thus, the study of the vulnerability of containerized and bulk shipping to acts of piracy and terrorism is important for the global economy. Current maritime threats vary from the possible hijacking of a commercial vessel to ramming an explosive-packed small boat into a ship, as in the 2000 attack on the USS *Cole (*DDG-67) (Carafano, 2007).

> Maritime infrastructure and transportation systems are critical and costly engineering systems that enable economic activity through the transfer of goods and services between national and international destinations. The impact of maritime systems on the economy is so essential that some consider the U.S. as a maritime country. For example, in 2003 approximately 95% of the volume of American overseas trade critical to nation's economic health was carried by maritime systems, mostly in containers. (Mansouri, 2009)

Worldwide maritime routes are currently threatened by piracy. During 2011, there were 439 attacks, with 45 vessels hijacked, 176 boarded, 113 fired upon, and 105 reports of attempted attacks. 237 of these attacks were mounted by Somali pirates. Most of these attacks took place within the intersection of the Gulf of Aden and the Arabian Sea, crossed by some of the busiest routes in the world (International Chamber of Commerce, 2012). Piracy off the coast of Somalia has been estimated to cost over $15 billion per year in global trade since 2005 (Nicholson, 2011). Attacks have also been reported in other regions of the globe, such as Southeast Asia, the Indian subcontinent and Nigeria. Examining a world maritime route map, it is possible to note other vulnerable bottlenecks for maritime traffic, such as the Panama and Suez Canals and the Strait of Gibraltar.

This research develops and implements network interdiction-optimization models (see, e.g., Brown et al., 2005) in order to (a) assess the resiliency of the world's maritime network to the disruption of a few maritime routes at strategic chokepoints; (b) recommend alternative routes in case of disruption; and (c) analyze the cost of using

alternative routes. Specifically we answer the following question: What subset(s) of interdicted seaways would be most critical to global maritime trade and what would be the relative level of disruption?

Though certain natural threats, such as tsunamis, may also disrupt existing maritime routes, this research focuses on manmade disruption caused by either:

1. Piracy, consisting of small terrorist groups, usually seeking to seize the cargo or capture the vessel's crew until a ransom is paid; or,
2. Political, such as a country's decision to block access of commercial vessels to nearby international waters.

B. LITERATURE REVIEW

> Transportation networks play a crucial role in areas as diverse as human mobility, the exchange of goods, and the spread of invasive species. With 90% of world trade carried by sea, the global network of merchant ships provides an essential mode of transportation. The network has several features that set it apart from other transportation networks. The network of all ship movements possesses a heavy-tailed distribution for the connectivity of ports and for the loads transported on the links with systematic differences between ship types. (Kaluza, 2010)

Lee, Chew, and Lee (2006), develop a multi-commodity network flow model to estimate the demand at the ports of the Asia-Pacific region. Their model, like the one described in this thesis, is based on a premise that shippers attempt to minimize total logistics costs. However, they do not assess interdictions.

Attacker–defender (AD) models are extensively used in network interdiction problems to assess worst-case disruption to the maximum flow of commodities through a capacitated network. Bard and Moore (1990) introduce techniques to solve an AD, mixed-integer, linear program (MIP) as a bilevel model. They develop an algorithm that can approximate this problem heuristically.

Network interdiction has applications including homeland security and counter–drug operations. In Wood (1993), the author introduces a mathematical model to solve deterministic shortest path network interdiction. The model is applied to anti-drug smuggling operations where the main focus is the intercept of chemicals used in drug production. Wood provides a MIP formulation for a discrete interdiction problem, and

provides an extension of the model to allow for continuous interdiction, multiple sources and sinks, undirected networks, multiple interdiction resources, and multiple commodities. This work was extended by Cormican et al. (1998), to model an attacker seeking to minimize the expected maximum flow, given uncertainties in the success of interdiction and arc capacities.

On military applications, Washburn and Wood (1995) build a model that represents a situation in which a single evader attempts to traverse a path between two nodes in a network while a single "inspector" tries to detect the evader by setting up inspection points along the network arcs. The problem for the inspector is to find a strategy that maximizes the probability of detecting the evader, while the problem for the evader is to find a strategy that minimizes the interdiction probability. Washburn and Wood formulate this problem as a two-person, zero-sum matrix game, then show how it can be solved using a maximum-flow network model.

Isreali and Wood (2002) describe a shortest-path network interdiction problem and formulate it using a bilevel MIP. They formulate a bilevel, max–min AD problem. The resulting MIP can be solved directly, but they develop more efficient decomposition algorithms.

Brown et al. (2006) develop bilevel (AD and defender–attacker) and trilevel (defender–attacker–defender) optimization models for the defense of critical infrastructure. They apply these models to many real-world examples, such as a strategic petroleum reserve, electric power grids, and supply chains, to highlight any vulnerability in these infrastructures. They show the benefits of such models in helping decision makers to make appropriate defensive plans.

Bencomo (2009) proposes a model to provide a capability to assess the economic impacts on import and export container flows of various types of disruptions to ports or to the U.S. domestic transportation system (rail or truck). He introduces a tool to represent container flows and the potential changes in these flows under a variety of conditions (port disruptions, extensive security-related delays, natural disasters, and so forth). The tool includes available data on container movements, estimation of origin–

destination matrices for international container flows entering or leaving the U.S., and development of a network model to represent container movements, both internationally and domestically. The international-network model allows flow diversions between U.S. ports due to the implementation of security initiatives or port disruptions. The author uses a multi-commodity, network flow model that finds paths through the network for shipments to minimize their total logistics cost, in travel days, which affects transportation and inventory costs. He uses an AD model to represent a transportation network subject to interdiction. The model allows the attacker to first attack the network, and then the defender optimally alters the flow of containers on the surviving network components.

The work of Pidgeon (2008) introduces a simulation model to identify and measure the effects of congestion at container ports on the west coast of the U.S., and shipper costs, subsequent to a transportation-security incident (TSI) upon these ports and the marine-transportation system. Pidgeon identifies and quantifies the disruption and incremental costs following a TSI at these container ports. He identifies which ports contain infrastructure components that are potential bottlenecks or are vulnerable to a TSI that threatens maritime shipping capacities, thus indicating they would benefit from incremental investments or government subsidies.

II. DATA

A. CARGO VOLUME

In order to create an approximated worldwide maritime traffic network, it is necessary to estimate the amount of cargo transported to and from each port, and the sea routes (arcs) between nodes (ports and at-sea locations) used by the vessels.

We use graphical information (see, e.g., Figures 1 and 2) and specific data on cargo volume to establish a network that represents global maritime routes and ports. Then, using available data and a "gravity model" of flow (described later in this chapter), we estimate cargo movements between each pair of ports.

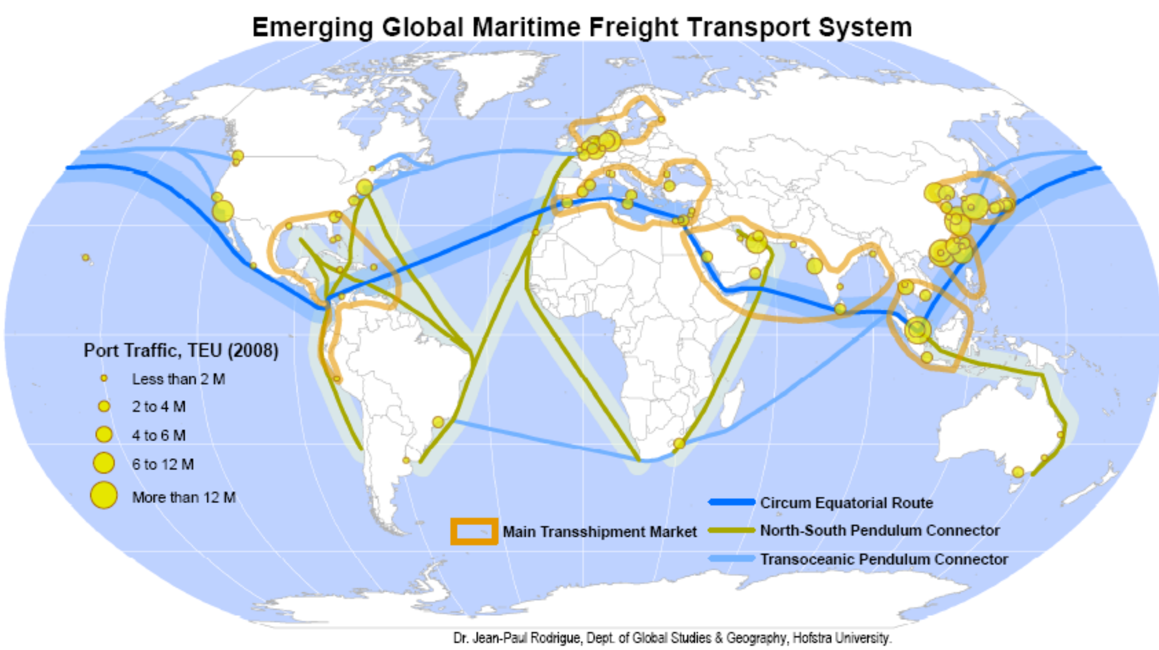

Figure 1. Main maritime shipping routes (From Rodrigue, 2012a)

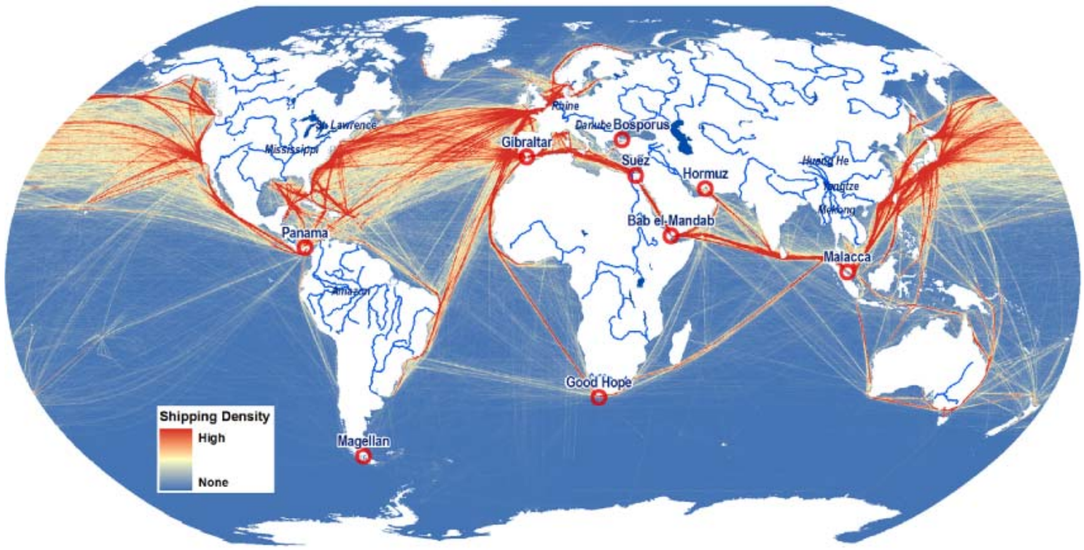

Figure 2. Domains of maritime circulation (From Rodrigue, 2012b)

We consider the most important ports in the world, based on the amount of cargo processed, as specified by the American Association of Port Authorities (AAPA, 2012). Specifically, the AAPA has published a ranking of the 125 most important ports according to the total (outgoing and incoming) volume of cargo in 2008. However, the U.S. ports of Tampa, Texas City, and Corpus Christi are duplicated on the list, so we keep one of each. Furthermore, the ports of Duluth and Pittsburgh are inner ports (located on the banks of rivers), without connection to the ocean, so we erase them from our list of interest. The final list comprises 120 ports.

Unfortunately, no separated information of incoming and outgoing volume has been found. As a surrogate for that information, we use the dollar export–import ratio (trade balance) of the country where the port is located. These data have been obtained from the Central Intelligence Agency (CIA, 2012).

The reader is cautioned that the relation between the incoming and outgoing cargo volumes of a port is not necessarily the same as the trade-balance ratio, because the value of the imports and exports of a given country are not necessarily proportional to the volumes of cargo involved. For example, those can represent technology and services, which are not a "cargo." In addition, the total of exports and imports is not entirely

commercialized through the maritime ports of the country: they can use aerial or ground alternatives, especially for trading with neighboring countries.

Table 1 shows the values (in billions of dollars) of imports and exports for year 2010, and the trade balance for every country with ports included in our model.

Table 1. Values (in billions of dollars) of imports and exports, and trade balances for year 2010

Country	Exports 2010 ($ billion)	Imports 2010 ($ billion)	Exports/Imports trade balance
Australia	212.90	194.70	1.09
Belgium	282.30	284.60	0.99
Brazil	201.90	181.70	1.11
Canada	393.00	401.70	0.98
China	1,578.00	1,327.00	1.19
Egypt	25.02	51.54	0.49
France	517.20	588.40	0.88
Germany	1,303.00	1,099.00	1.19
India	225.60	357.70	0.63
Indonesia	158.10	127.40	1.24
Italy	448.40	473.10	0.95
Japan	730.10	639.10	1.14
Korea South	464.30	422.40	1.10
Malaysia	197.00	152.60	1.29
Netherlands	486.70	429.50	1.13
Norway	132.70	74.30	1.79
Pakistan	24.90	32.88	0.76
Philippines	50.68	61.07	0.83
Romania	49.41	57.22	0.86
Russia	400.40	248.70	1.61
Saudi Arabia	237.90	88.35	2.69
Singapore	358.40	310.40	1.15
South Africa	85.70	81.86	1.05
Spain	253.00	315.30	0.80
Sweden	160.40	149.50	1.07
Turkey	120.90	177.30	0.68
Ukraine	52.19	60.90	0.86
U.K.	410.20	563.20	0.73
U.S.	1,289.00	1,935.00	0.67

Outgoing and incoming cargo volumes for each port i are calculated using the following formulae:

$$O_i = \frac{T_i}{1 + 1/R_i} \qquad [1]$$

$$I_i = \frac{T_i}{1 + R_i} \qquad [2]$$

where:

O_i	outgoing cargo volume of port i	[thousands of tons]
I_i	incoming cargo volume of port i	[thousands of tons]
T_i	total cargo of port i (see Table 2)	[thousands of tons]
R_i	exports/imports ratio of the country having port i (see Table 1) [fraction]	

Results for outgoing and incoming volume from and to each port using equations (1) and (2) are shown in Table 2.

Table 2. Annual outgoing and incoming cargo volume for each port.

Country	Port	Total cargo (tons × 1000)	Outgoing cargo (tons × 1000)	Incoming cargo (tons × 1000)
Australia	Hedland	159,391	83,254	76,137
Australia	Dampier	140,823	73,555	67,268
Australia	Newcastle	95,839	50,059	45,780
Australia	Hay Point	82,519	43,102	39,417
Australia	Gladstone	78,801	41,160	37,641
Australia	Brisbane	31,894	16,659	15,235
Belgium	Antwerp	189,390	94,311	95,079
Belgium	Zeebrugge	42,024	20,927	21,097
Brazil	Itaqui	105,187	55,363	49,824

Country	Port	Total cargo (tons × 1000)	Outgoing cargo (tons × 1000)	Incoming cargo (tons × 1000)
Brazil	Tubarao	99,873	52,566	47,307
Brazil	Sepetiba	84,888	44,679	40,209
Brazil	Santos	81,058	42,663	38,395
Brazil	Sao Sebastiao	49,759	26,190	23,569
Brazil	Paranagua	33,005	17,372	15,633
Brazil	Angra dos Reis	30,425	16,014	14,411
Canada	Vancouver	114,574	56,660	57,914
China	Qingdao	278,271	151,157	127,114
China	Qinhuangdao	252,000	136,887	115,113
China	Shanghai	508,000	275,946	232,054
China	Tianjin	365,163	198,357	166,806
China	Ningbo	361,850	196,557	165,293
China	Guangzhou	347,000	188,491	158,509
China	Hong Kong	259,402	140,908	118,494
China	Dalian	246,000	133,628	112,372
China	Shenzhen	211,000	114,615	96,385
China	Rizhao	151,000	82,023	68,977
China	Yingkou	151,000	82,023	68,977
China	Nantong	132,000	71,703	60,297
China	Yantai	112,000	60,839	51,161
China	Nanjing	111,000	60,295	50,705
China	Tangshan	109,000	59,209	49,791
China	Lianyungang	101,000	54,863	46,137
China	Kaohsiung	146,729	79,703	67,026
China	Taichung	52,203	28,357	23,846
Egypt	Alexandria and El-Dekheila	44,912	14,677	30,235
France	Marseilles	96,009	44,913	51,096
France	Le Havre	80,527	37,671	42,856
France	Dunkirk	57,692	26,988	30,704
France	Calais	39,709	18,576	21,133
Germany	Hamburg	140,375	76,148	64,227
Germany	Bremen	74,647	40,493	34,154
Germany	Wilhelmshaven	40,309	21,866	18,443
Germany	Lubeck	31,551	17,115	14,436
India	Madras (Chennai)	57,497	22,238	35,259
India	Jawaharlal Nehru	57,280	22,154	35,126

Country	Port	Total cargo (tons × 1000)	Outgoing cargo (tons × 1000)	Incoming cargo (tons × 1000)
India	Calcutta	54,051	20,905	33,146
India	Bombay	51,876	20,064	31,812
India	Paradip	46,412	17,951	28,461
India	Mormugao	41,680	16,120	25,560
India	New Mangalore	36,690	14,190	22,500
Indonesia	Tanjung Priok	42,050	23,286	18,764
Italy	Genoa	54,218	26,382	27,836
Italy	Trieste	48,279	23,492	24,787
Italy	Taranto	43,271	21,056	22,215
Italy	Leghorn	34,028	16,558	17,470
Japan	Nagoya	218,130	116,314	101,816
Japan	Chiba	165,143	88,059	77,084
Japan	Yokohama	141,764	75,593	66,171
Japan	Kitakyushu	109,367	58,318	51,049
Japan	Kobe	95,186	50,756	44,430
Japan	Osaka	92,976	49,578	43,398
Japan	Tokyo	81,328	43,367	37,961
Korea South	Busan	241,683	126,552	115,131
Korea South	Ulsan	170,279	89,163	81,116
Korea South	Inchon	141,815	74,258	67,557
Korea South	Pohang	67,657	35,427	32,230
Malasyia	Kelang	152,348	85,848	66,500
Malasyia	Tanjung Pelepas	87,939	49,554	38,385
Netherlands	Rotterdam	421,136	223,714	197,422
Netherlands	Amsterdam	94,768	50,342	44,426
Norway	Bergen	52,428	33,610	18,818
Pakistan	Karachi	37,193	16,028	21,165
Philippines	Manila	45,230	20,512	24,718
Romania	Constantza	61,837	28,654	33,183
Russia	Novorossisk	81,633	50,356	31,277
Russia	Primorsk	75,582	46,623	28,959
Russia	St. Petersburg	59,945	36,977	22,968
Saudi Arabia	Jubail	42,460	30,962	11,498
Saudi Arabia	Yanbu	37,509	27,351	10,158
Saudi Arabia	Jeddah	45,721	33,340	12,381

Country	Port	Total cargo (tons × 1000)	Outgoing cargo (tons × 1000)	Incoming cargo (tons × 1000)
Singapore	Singapore	515,415	276,203	239,212
South Africa	Richards Bay	84,534	43,236	41,298
South Africa	Saldanha Bay	46,532	23,799	22,733
South Africa	Durban	41,403	21,176	20,227
Spain	Algeciras - La Linea	69,572	30,973	38,599
Spain	Valencia	59,425	26,455	32,970
Spain	Barcelona	50,545	22,502	28,043
Spain	Bilbao	37,980	16,908	21,072
Spain	Tarragona	32,969	14,677	18,292
Sweden	Gothenburg	43,241	22,381	20,860
Turkey	Izmit (Kocaeli)	53,852	21,833	32,019
U.K.	Grimsby and Immingham	65,267	30,120	35,147
U.K.	London	52,965	24,443	28,522
U.K.	Tees and Hartlepool	45,436	20,968	24,468
U.K.	Southampton	40,974	18,909	22,065
U.K.	Forth	39,054	18,023	21,031
U.K.	Milford Haven	35,875	16,556	19,319
U.K.	Liverpool	32,204	14,862	17,342
Ukraine	Odessa	34,562	14,565	19,997
U.S.	South Louisiana	203,157	81,225	121,932
U.S.	Houston	192,473	76,953	115,520
U.S.	New York/New Jersey	139,207	55,657	83,550
U.S.	Corpus Christi	79,079	31,617	47,462
U.S.	Long Beach	72,746	29,085	43,661
U.S.	New Orleans	66,221	26,476	39,745
U.S.	Beaumont	63,022	25,197	37,825
U.S.	Huntington	62,887	25,143	37,744
U.S.	Mobile	61,345	24,527	36,818
U.S.	Hampton Roads	60,947	24,367	36,580
U.S.	Plaquemines	57,816	23,116	34,700
U.S.	Los Angeles	161,900	64,730	97,170
U.S.	Lake Charles	48,777	19,502	29,275
U.S.	Texas City	47,714	19,077	28,637
U.S.	Baton Rouge	46,991	18,788	28,203

Country	Port	Total cargo (tons × 1000)	Outgoing cargo (tons × 1000)	Incoming cargo (tons × 1000)
U.S.	Tampa	42,613	17,037	25,576
U.S.	Baltimore, MD	39,375	15,743	23,632
U.S.	Paulsboro	32,971	13,182	19,789
U.S.	Valdez	32,622	13,043	19,579
U.S.	Savannah	32,102	12,835	19,267
U.S.	Pascagoula	30,466	12,181	18,285

The next step consists of finding the volume of cargo from each port to the remaining 119 ports. No information has been found from the AAPA regarding destinations and the volume of cargo that navigates towards each destination, or the procedence and quantity of the cargo that arrives to each port. Therefore, these data have been inferred using the CIA's World Factbook, which provides partial information about the destination of the exports and the origin of the importations for the countries involved in this model (see Tables 3 and 4).

Table 3. Export partners by country.

Country	Export partners
Australia	China 25.1%, Japan 18.9%, South Korea 8.9%, India 7.1%, U.S. 4%
Belgium	Germany 19.1%, France 17%, Netherlands 12.2%, U.K. 7.2%, U.S. 5.3%, Italy 4.7%
Brazil	China 15.2%, U.S. 9.6%, Argentina 9.2%, Netherlands 5.1%, Germany 4%
Canada	U.S. 74.9%, U.K. 4.1%
China	U.S. 18%, Hong Kong 13.8%, Japan 7.6%, South Korea 4.4%, Germany 4.3%
Egypt	U.S. 7.6%, Italy 7.3%, India 6.1%, Spain 5.4%, Saudi Arabia 5.4%, France 4.7%, Libya 4%
France	Germany 16.4%, Italy 8.2%, Belgium 7.7%, Spain 7.6%, U.K. 6.8%, U.S. 5.1%, Netherlands 4.2%
Germany	France 10.1%, U.S. 6.7%, U.K. 6.6%, Netherlands 6.6%, Italy 6.3%, Austria 5.7%, Belgium 5.2%, China 4.7%, Switzerland 4.5%

Country	Export partners
India	U.S. 12.6%, UAE 12.2%, China 8.1%, Hong Kong 4.1%
Indonesia	Japan 16.3%, China 10%, U.S. 9.1%, Singapore 8.7%, South Korea 8%, India 6.3%, Malaysia 5.9%
Italy	Germany 13.2%, France 11.7%, Spain 5.9%, U.S. 5.8%, U.K. 5.4%, Switzerland 4.6%
Japan	China 19.4%, U.S. 15.7%, South Korea 8.1%, Hong Kong 5.5%, Thailand 4.4%
Korea South	China 27.9%, U.S. 10.2%, Japan 5.8%
Malaysia	Singapore 13.4%, China 12.6%, Japan 10.4%, U.S. 9.5%, Thailand 5.3%, Hong Kong 5.1%
Netherlands	Germany 26%, Belgium 13%, France 9.2%, U.K. 7.7%, Italy 4.9%
Norway	U.K. 26.7%, Netherlands 12.1%, Germany 11.4%, Sweden 7%, France 6.6%, U.S. 5%
Pakistan	U.S. 15.8%, Afghanistan 8.1%, UAE 7.9%, China 7.3%, U.K. 4.3%, Germany 4.2%
Philippines	China 19%, U.S. 13.4%, Singapore 13.2%, Japan 12.8%, Hong Kong 7.6%, Germany 4.2%, South Korea 4.1%
Romania	Germany 18.4%, Italy 14.1%, France 8.5%, Turkey 6.9%, Hungary 4.9%
Russia	Germany 8.2%, Netherlands 6%, U.S. 5.6%, China 5.4%, Turkey 4.6%
Saudi Arabia	Japan 14.3%, China 13.1%, U.S. 13%, South Korea 8.8%, India 8.3%, Singapore 4.5%
Singapore	Malaysia 11.9%, Hong Kong 11.7%, China 10.4%, Indonesia 9.4%, U.S. 6.5%, Japan 4.7%, South Korea 4.1%
South Africa	China 13.7%, U.S. 10.1%, Japan 8.7%, Germany 7.3%, U.K. 7.1%, India 4.3%
Spain	France 18.7%, Germany 10.7%, Portugal 9.1%, Italy 9%, U.K. 6.3%
Sweden	Germany 10.5%, Norway 9.8%, U.K. 7.8%, Denmark 6.9%, Finland 6.5%, U.S. 6.4%, Netherlands 5.2%, France 5.2%, Belgium 4.3%
Turkey	Germany 10.1%, U.K. 6.4%, Italy 5.7%, France 5.3%, Iraq 5.3%, Russia 4.1%
Ukraine	Russia 24.1%, Turkey 5.9%, Italy 4.7%
U.K.	U.S. 11.4%, Germany 11.2%, Netherlands 8.5%, France 7.7%, Ireland 6.8%, Belgium 5.4%
U.S.	Canada 19.4%, Mexico 12.8%, China 7.2%, Japan 4.7%

Table 4. Import partners by country.

Country	Import partners
Australia	China 18.7%, U.S. 11.1%, Japan 8.7%, Thailand 5.2%, Singapore 5.1%, Germany 5%, Malaysia 4.3%
Belgium	Netherlands 19.1%, Germany 16.4%, France 11.3%, U.K. 5.4%, U.S. 5.3%, Ireland 5.3%, China 4.1%
Brazil	U.S. 15%, China 14.1%, Argentina 7.9%, Germany 6.9%, South Korea 4.6%
Canada	U.S. 50.4%, China 11%, Mexico 5.5%
China	Japan 12.6%, South Korea 9.9%, U.S. 7.3%, Germany 5.3%, Australia 4.3%
Egypt	U.S. 11.8%, China 10.4%, Germany 6.5%, Italy 6.4%, Saudi Arabia 4.1%
France	Germany 19.3%, Belgium 11.4%, Italy 8%, Netherlands 7.5%, Spain 6.8%, China 5.1%, U.K. 5%
Germany	Netherlands 13%, France 8.2%, Belgium 7.2%, China 6.8%, Italy 5.6%, U.K. 4.7%, Austria 4.4%, U.S. 4.2%, Switzerland 4.1%
India	China 12.4%, UAE 6.5%, Saudi Arabia 5.8%, U.S. 5.7%, Australia 4.5%
Indonesia	China 15.1%, Singapore 14.9%, Japan 12.5%, U.S. 6.9%, Malaysia 6.4%, South Korea 5.7%, Thailand 5.5%
Italy	Germany 16.2%, France 8.5%, China 7.9%, Netherlands 5.4%, Spain 4.5%
Japan	China 22.1%, U.S. 9.9%, Australia 6.5%, Saudi Arabia 5.2%, UAE 4.2%, South Korea 4.1%, Indonesia 4.1%
Korea South	China 17.9%, Japan 16.2%, U.S. 10.1%, Saudi Arabia 5.2%, Australia 4.9%
Malaysia	China 12.6%, Japan 12.6%, Singapore 11.4%, U.S. 10.7%, Thailand 6.2%, Indonesia 5.6%
Netherlands	Germany 15.5%, China 12.6%, Belgium 8.3%, U.S. 6.8%, U.K. 6.2%, Russia 5.6%
Norway	Sweden 14.1%, Germany 12.4%, China 8.5%, Denmark 6.3%, U.K. 5.9%, U.S. 5.4%
Pakistan	UAE 16.3 %, Saudi Arabia 12.5 %, China 11.6 %, Kuwait 8.4 %, Singapore 7.1 %, Malaysia 5%
Philippines	Japan 14.1%, China 13.6%, U.S. 9.9%, Singapore 9.3%, Thailand 6.5%, South Korea 5.6%, Indonesia 4.1%
Romania	Germany 16.8%, Italy 11.6%, Hungary 8.7%, France 6%, China 5.5%, Russia 4.4%, Austria 4.1%
Russia	Germany 14.7%, China 13.5%, Ukraine 5.5%, Italy 4.7%, Belarus 4.5%
Saudi Arabia	U.S. 12.4%, China 11.1%, Germany 7.1%, Japan 6.9%, France 6.1%, India 4.7%, South Korea 4.2%
Singapore	South Africa 14.7%, China 10.7%, Malaysia 6.7%, U.S. 6.6%, U.K. 6.4%, Cote dIvoire 5.7%, India 4.8%

Country	Import partners
South Africa	China 13.4%, Germany 11.2%, U.S. 7%, Saudi Arabia 5.3%, Japan 4.7%, Iran 4.3%, U.K. 4.3%
Spain	Germany 12.6%, France 11.5%, Italy 7.3%, China 6.8%, Netherlands 5.6%, U.K. 4.9%
Sweden	Germany 18.3%, Norway 8.5%, Denmark 8.3%, Netherlands 6.2%, U.K. 5.7%, Finland 5.4%, China 4.9%, Russia 4.9%, France 4.7%
Turkey	Russia 11.6%, Germany 9.5%, China 9.3%, U.S. 6.6%, Italy 5.5%, France 4.4%, Iran 4.1%
Ukraine	Russia 33.9%, China 8.5%, Germany 8.1%, Poland 5.4%, Belarus 4.1%
U.K.	Germany 13.1%, China 9.1%, Netherlands 7.5%, France 6.1%, U.S. 5.8%, Norway 5.5%, Belgium 4.9%
U.S.	China 19.5%, Canada 14.2%, Mexico 11.8%, Japan 6.3%, Germany 4.3%

As shown in those tables, percentages of imports and exports for some countries are given. However, these percentages do not cover 100% of each country's trading; thus, the missing fraction will be inferred using a gravity model (described below).

With all the data processed as above, two matrices have been created: one for export percentages, and another for import percentages. An excerpt of these matrices is shown in Tables 5 and 6. Blanks indicate data are not available.

Table 5. Excerpt of approximated exports between countries (fraction). For example, Australia exports 25.1% of its volume to China.

Exports	Australia	Belgium	Brazil	Canada	China	Egypt	France	Germany
Australia					0.251			
Belgium							0.170	0.191
Brazil					0.152			0.040
Canada								
China								0.043
Egypt							0.047	
France		0.077						0.164
Germany		0.052			0.047		0.101	

Table 6. Excerpt of approximated imports between countries (fraction). For example, Australia imports 18.7% of its volume from China.

Imports	Australia	Belgium	Brazil	Canada	China	Egypt	France	Germany
Australia					0.187			0.050
Belgium					0.041		0.113	0.164
Brazil					0.141			0.069
Canada					0.110			
China	0.043							0.053
Egypt					0.104			0.065
France		0.114			0.051			0.193
Germany		0.072			0.068		0.082	

B. GRAVITY MODEL IN MARITIME TRADE

A gravity model, as scientists refer to the modified Newton's law of universal gravitation, is a method used to approximate certain behaviors that mimic gravitational interaction. A gravity model incorporates the idea that larger places attract more people, ideas, and commodities than do smaller places, and places closer together also have a greater attraction.

Our gravity model of trade, applied to international commerce, estimates the flow of bilateral commerce based on population and distance between two countries. A similar model was first used by Tinbergen in 1962 to explain international bilateral trade (Nello, 2009). The model has also been used to test the effectiveness of trade agreements and organizations such as the North American Free Trade Agreement and the World Trade Organization.

The basic theoretical model for trade between two countries (*p* and *q*) takes the form of:

$p, q \in P$ countries

pop_p population of country *p* [millions of people]

$dist_{p,q}$ shortest ocean distance between countries *p* and *q* [n.m.]

$gravity_{p,q}$ normalized level of trade between countries p and q [unitless]. Defined as:

$$gravity_{p,q} = \frac{\sqrt{pop_p pop_q} / dist_{p,q}}{G} \qquad \forall p \neq q \qquad [3]$$

where:

$$G = \sum_q \frac{\sqrt{pop_p pop_q}}{dist_{p,q}} \qquad \forall p \neq q \qquad [4]$$

The population of each country included in this model has been obtained from the Department of Economic and Social Affairs (United Nations, 2012).

Table 7. Population, latitude and longitude of countries included in our study

Country	Population (in millions)	Latitude	Longitude
Australia	22.268	-24.4213	140.1069
Belgium	10.712	51.2747	3.8021
Brazil	194.946	-25.2628	-47.6901
Canada	34.017	49.2612	-123.1140
China	1341.335	32.3459	119.1755
Egypt	81.121	31.1261	29.8159
France	62.787	48.6942	2.4279
Germany	82.302	53.6263	9.3430
India	1224.614	16.4117	83.0848
Indonesia	239.871	-6.1178	106.8698
Italy	60.551	43.5204	12.5651
Japan	126.536	35.0270	136.8450
Korea South	50.133	36.0483	128.6089
Malasyia	28.401	2.1939	102.4929
Netherlands	16.613	52.1417	4.7344
Norway	4.883	60.3913	5.3221
Pakistan	173.593	24.8934	67.0281
Philippines	93.261	14.5995	120.9842
Romania	21.486	44.1733	28.6383
Russia	142.958	53.1790	29.2998

Country	Population (in millions)	Latitude	Longitude
Saudi Arabia	27.448	24.2142	42.2965
Singapore	5.086	1.3521	103.8198
South Africa	50.133	-30.5483	27.0003
Spain	46.077	40.2710	-1.0673
Sweden	9.38	57.7089	11.9746
Turkey	72.752	40.7760	29.9484
U.K.	62.036	53.1333	-2.0137
Ukraine	45.448	46.4846	30.7326
U.S.	310.384	33.9800	-92.6375

Table 7 shows the population and latitude and longitude of all the countries included in this study. In order to calculate the distances between countries, we use the following great circle formula (see, e.g., Wikipedia, 2012):

$$dist_{p,q} = \text{Earth radious} \times \arccos[\sin(\text{lat}_p)\sin(\text{lat}_q) + \cos(\text{lat}_q)\cos(\text{long}_q - \text{long}_p)] \quad [5]$$

Finally, the gravity level of each country is used to populate the import- and export-percentage matrices in those cases where there is no information available from the CIA's website. See Tables 8 and 9.

Table 8. Excerpt of complete export percentage matrix (fraction). Highlighted entries are based on CIA data.

Export	Australia	Belgium	Brazil	Canada	China	Egypt	France	Germany
Australia	0.000	0.004	0.017	0.008	0.251	0.012	0.009	0.011
Belgium	0.002	0.000	0.008	0.004	0.024	0.017	0.170	0.191
Brazil	0.010	0.011	0.000	0.017	0.152	0.028	0.026	0.040
Canada	0.002	0.003	0.008	0.000	0.025	0.005	0.006	0.007
China	0.009	0.005	0.010	0.009	0.000	0.015	0.012	0.043
Egypt	0.004	0.013	0.016	0.006	0.053	0.000	0.047	0.036
France	0.003	0.077	0.013	0.007	0.037	0.027	0.000	0.164
Germany	0.002	0.052	0.010	0.006	0.047	0.022	0.101	0.000

Table 9. Excerpt of complete import percentage matrix (fraction). Highlighted entries are based on CIA data.

Import	Australia	Belgium	Brazil	Canada	China	Egypt	France	Germany
Australia	0.000	0.004	0.017	0.008	0.187	0.012	0.009	0.050
Belgium	0.002	0.000	0.007	0.004	0.041	0.015	0.113	0.164
Brazil	0.009	0.009	0.000	0.015	0.141	0.025	0.023	0.069
Canada	0.005	0.005	0.016	0.000	0.110	0.011	0.012	0.015
China	0.043	0.006	0.012	0.010	0.000	0.018	0.014	0.053
Egypt	0.004	0.012	0.015	0.006	0.104	0.000	0.029	0.065
France	0.002	0.114	0.011	0.006	0.051	0.023	0.000	0.193
Germany	0.002	0.072	0.009	0.005	0.068	0.021	0.082	0.000

The export datum of every country is then applied to the outgoing cargo volume of every port in a given country, in order to build a new matrix of cargo exports containing cargo volumes by port (in thousands of tons), instead of percentages by country. The same procedure allows us to build a matrix of cargo imports.

Because our model needs one matrix of demand, we calculate an average of the import and export values. We note that these two matrices need not to be identical, because we are combining data from different sources.

As a result, we obtain a matrix of 120 by 120 demands containing data of incoming cargo volumes, which we use in our model. The values of demand were originally expressed in thousands of tons per year; however, in our model, we convert them into tons per day.

C. ROUTES

The 120 ports constitute the initial set of nodes in our network. We add 35 waypoints at sea where necessary to change the trajectories of the great-circle routes to avoid mainlands. The list of additional nodes (waypoints) included in our network model, along with their latitude and longitude, is shown in Table 10.

For example, in order to allow tracing a route from the port of Hay Point, on the east coast of Australia, to the port of Hedland, on the west coast, the nodes of Horn Land and Darwin have been created, as shown in Figure 3.

Naturally, all waypoints are transshipment nodes, with no own supply or demand of any commodity.

Table 10. Additional waypoint nodes included in the network model

Waypoint name	Closest country	Latitude	Longitude
Aden	Yemen	11.1784	45.6152
BandaAceh	Indonesia	6.1406	94.9219
BosphorusN	Turkey	41.3768	29.2181
BosphorusS	Turkey	40.7847	28.8940
BrazilGroup	Brazil	-25.1652	-41.6602
Brest	France	48.8069	-5.4053
Caribe	Caribe	14.6048	-72.3779
Comoros	Mozanbique-Madagascar	-13.9661	43.7695
Corunna	Spain	43.8345	-9.8438
Crete	Greece	35.2097	26.4771
Dakar	Senegal	14.6048	-18.8086
Darwin	Australia	-10.4878	131.0889
GibraltarE	Spain	36.7741	-0.0439
GibraltarW	Spain	35.6037	-10.4590
HornIsland	Australia	-10.0013	142.5696
ItalyHeel	Italy	39.7410	19.0283
Jeju	South Korea	33.8522	126.5845
LombokN	Bali	-7.6021	116.0596
LombokS	Bali	-9.3840	115.6421
Magellan	Argentina	-57.1362	-67.9834
Messina	Italy	38.0438	15.5841
Myrina	Greece	39.5379	25.2246
Natal	Brazil	-5.3535	-34.0137
NorthSea	Denmark	56.7527	5.4492
Oman	Oman	23.4028	61.2158
PanamaE	Panama	10.3582	-79.4971
PanamaW	Panama	4.3026	-82.2656
Socotra	Somalia	12.9403	54.6680
SriLanka	Sri Lanka	6.1406	78.5742
SuezN	Egypt	31.8216	32.2119
SuezS	Egypt	28.9793	32.7832
SundaE	Indonesia	-4.8283	108.0615
SundaW	Indonesia	-7.1881	103.9307
USEastGroup	U.S.	38.4106	-70.4004
USSouthGroup	U.S.	22.5531	-84.8145

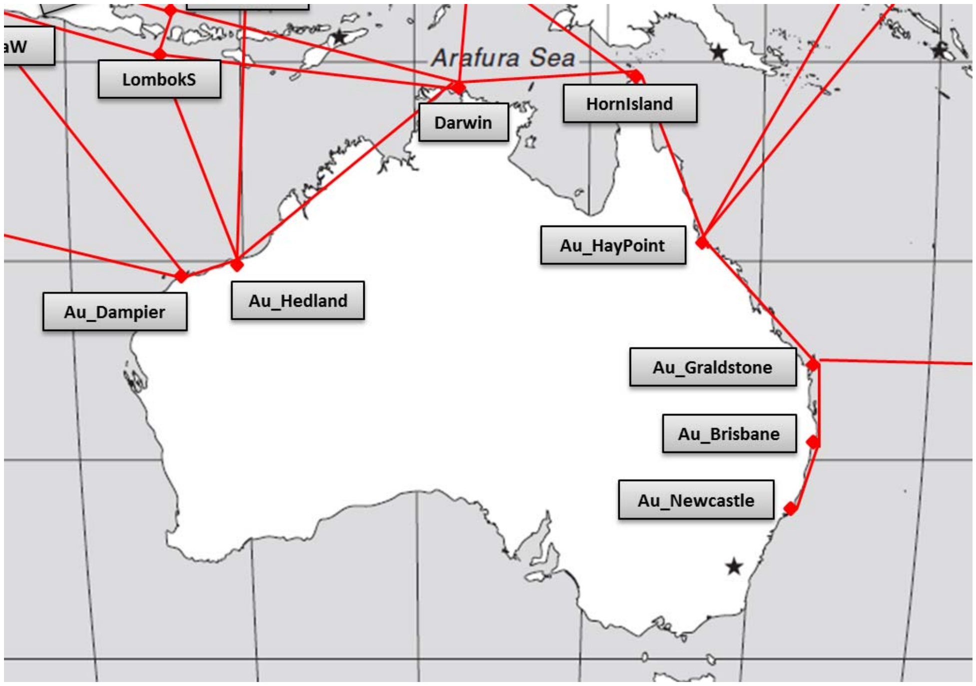

Figure 3. Waypoints Darwin and HornIland added to allow tracing sea routes.

Starting with the selected nodes (ports and waypoints), we create a number of arcs so all ports are connected. Each arc assumes the shortest great-circle distance between two nodes. To create the arcs, the world map is divided into seven zones:

1. North America,
2. South America,
3. Europe,
4. Southeast Asia and Oceania,
5. Central and Southwest Asia,
6. Korea and Japan, and
7. Africa.

Figures 4 to 10 show the routes in each zone of the world map. A total of 416 directed arcs—taking into account both directions of navigation along the same sea lane—are created.

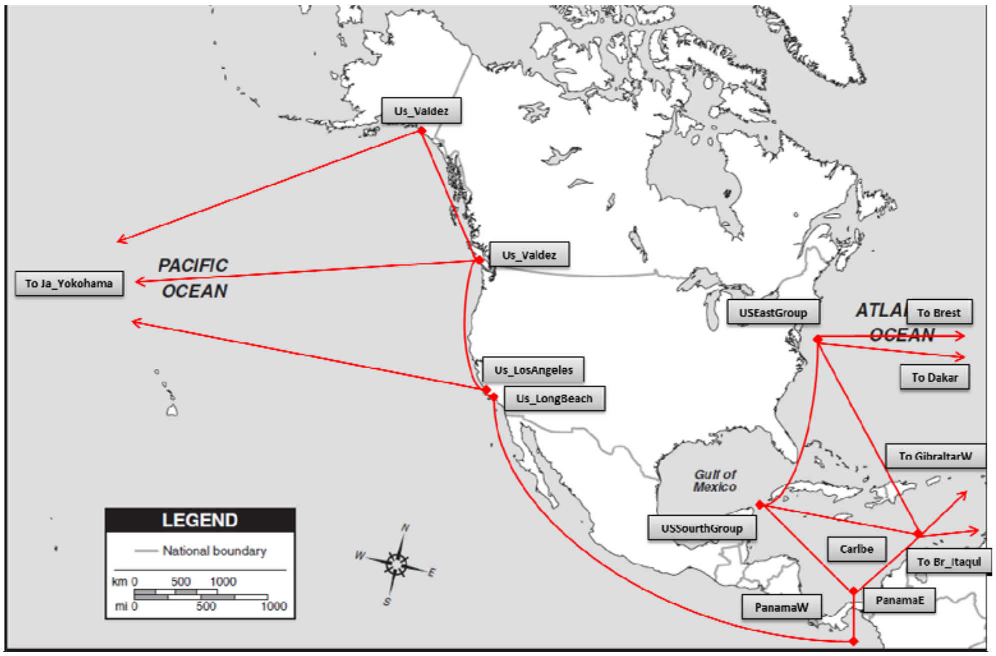

Figure 4. Arcs in North American zone

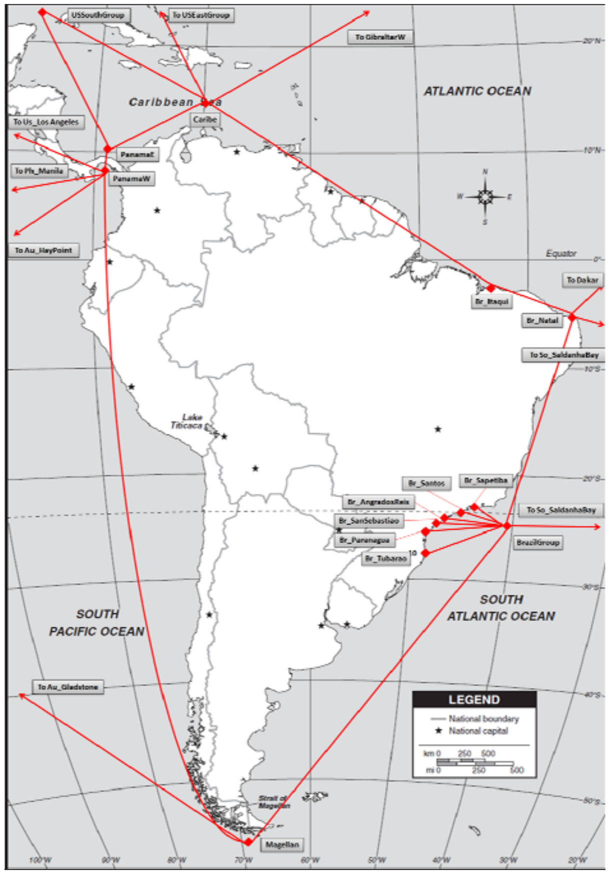

Figure 5. Arcs in South American zone

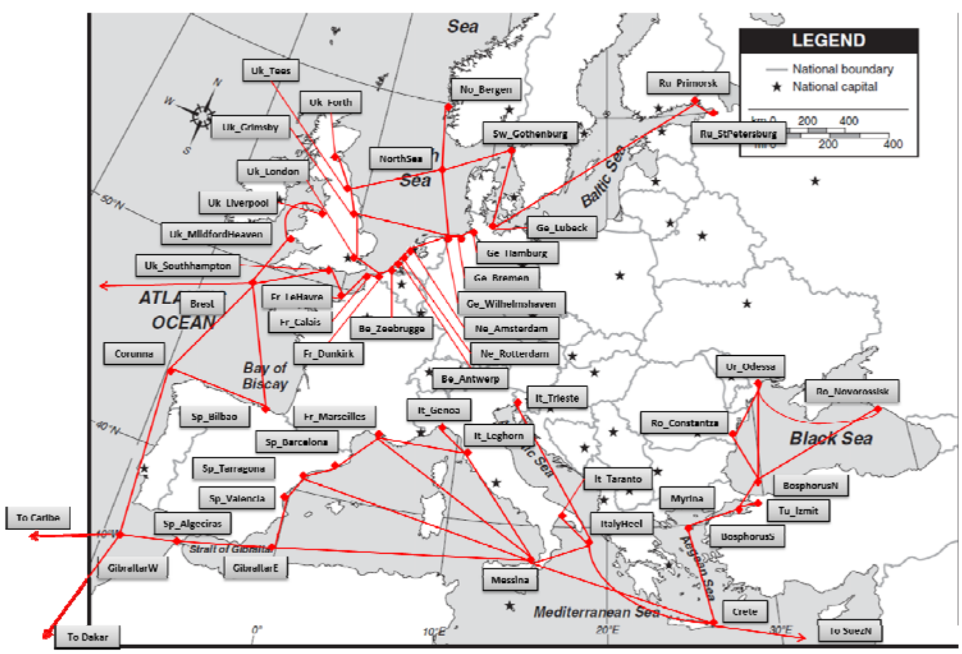

Figure 6. Arcs in European zone

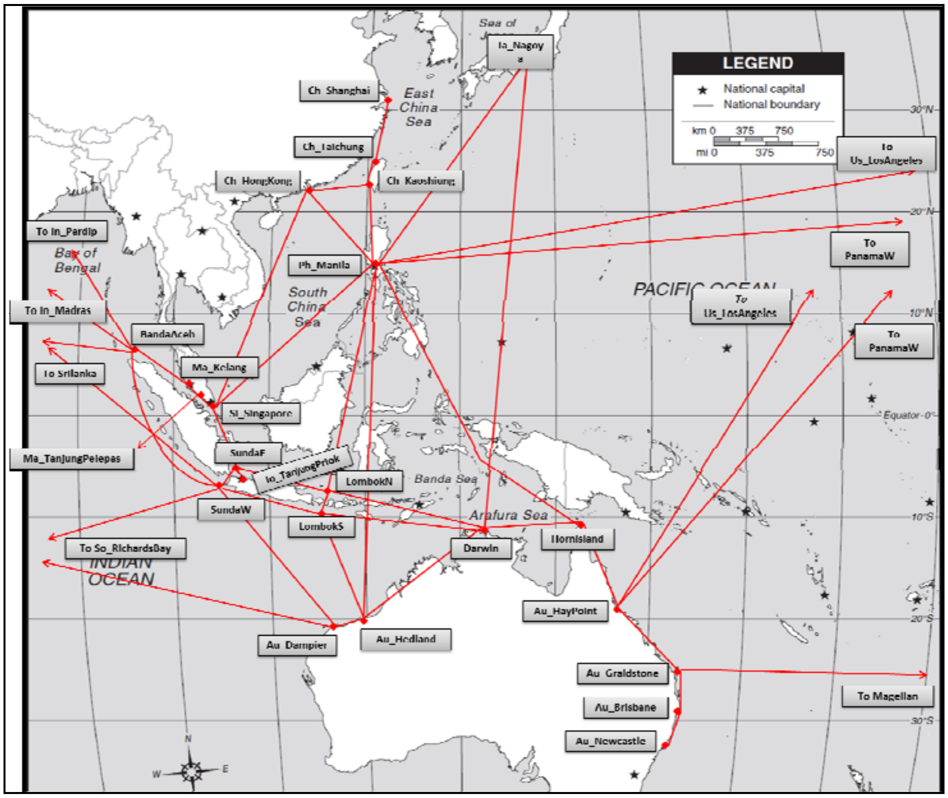

Figure 7. Arcs in Southeast Asian and Oceania zone

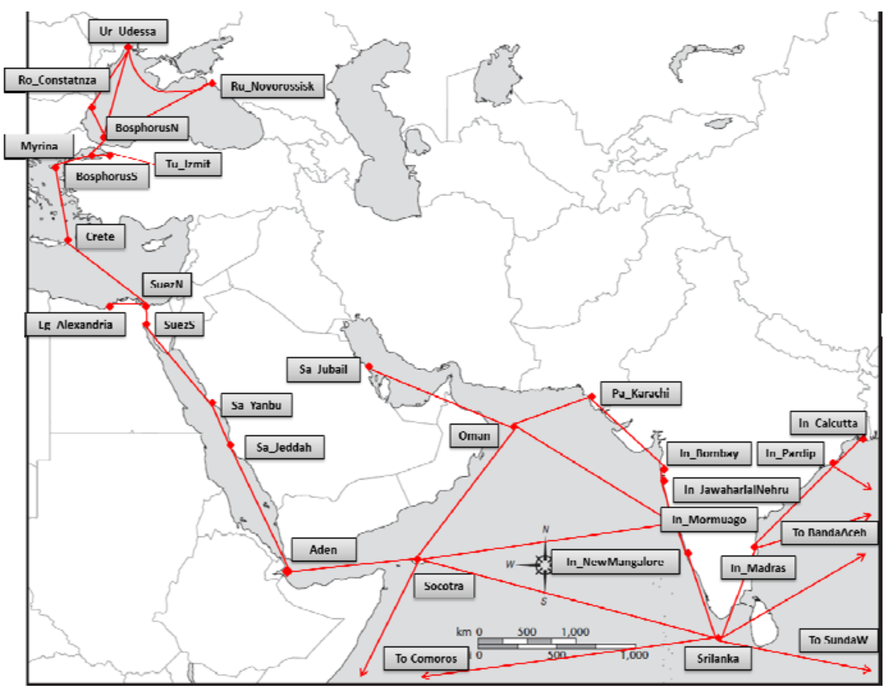

Figure 8. Arcs in Central and Southwest Asian zone

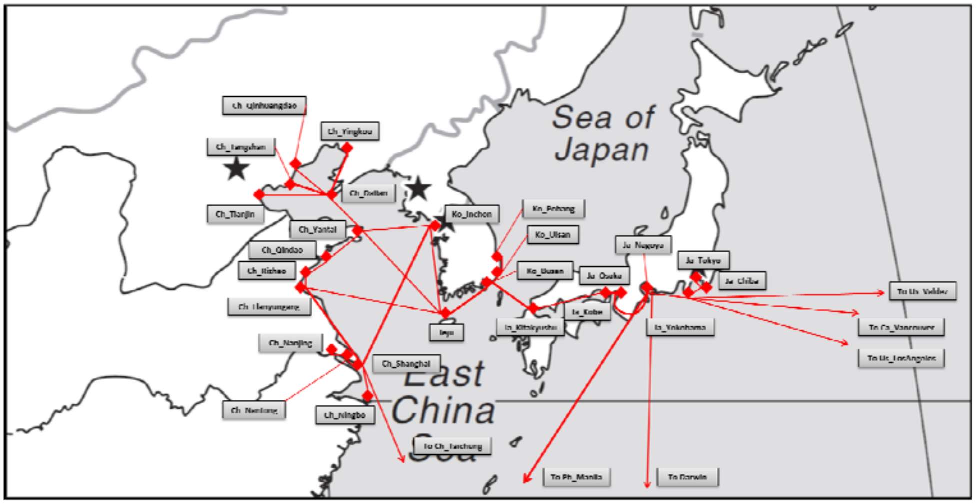

Figure 9. Arcs in Southeast Asian zone

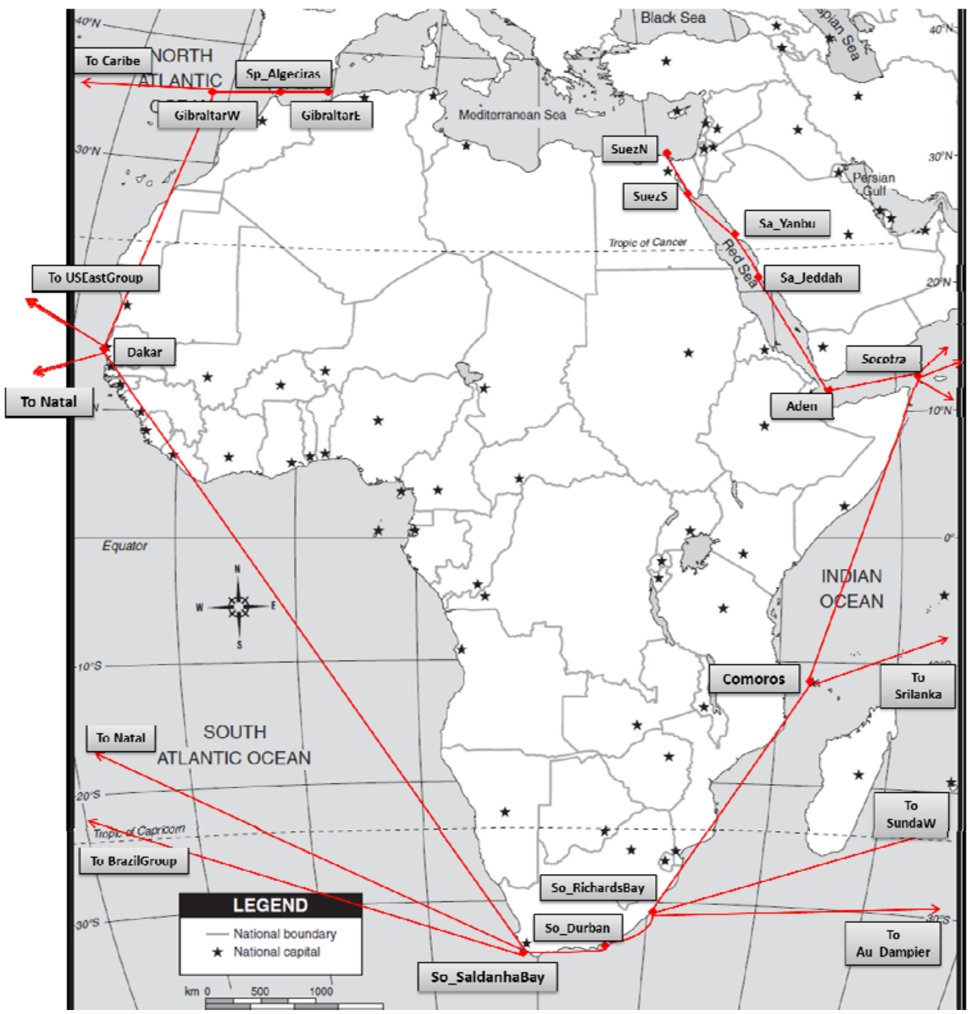

Figure 10. Arcs in African zone

In addition to waypoints in the open sea, we also create some waypoints that connect nearby ports. The purpose of this is to simplify tracing the routes. An example is the USEast Group and the USSouth Group, as shown on the North American map of arcs in Figures 11 and 12.

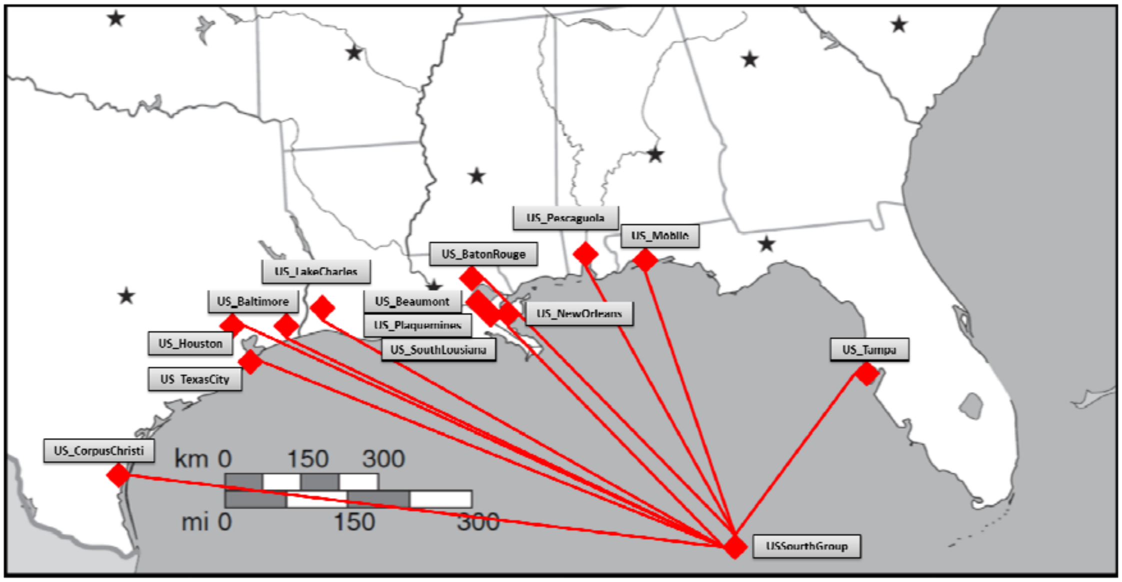

Figure 11. USEast Group node

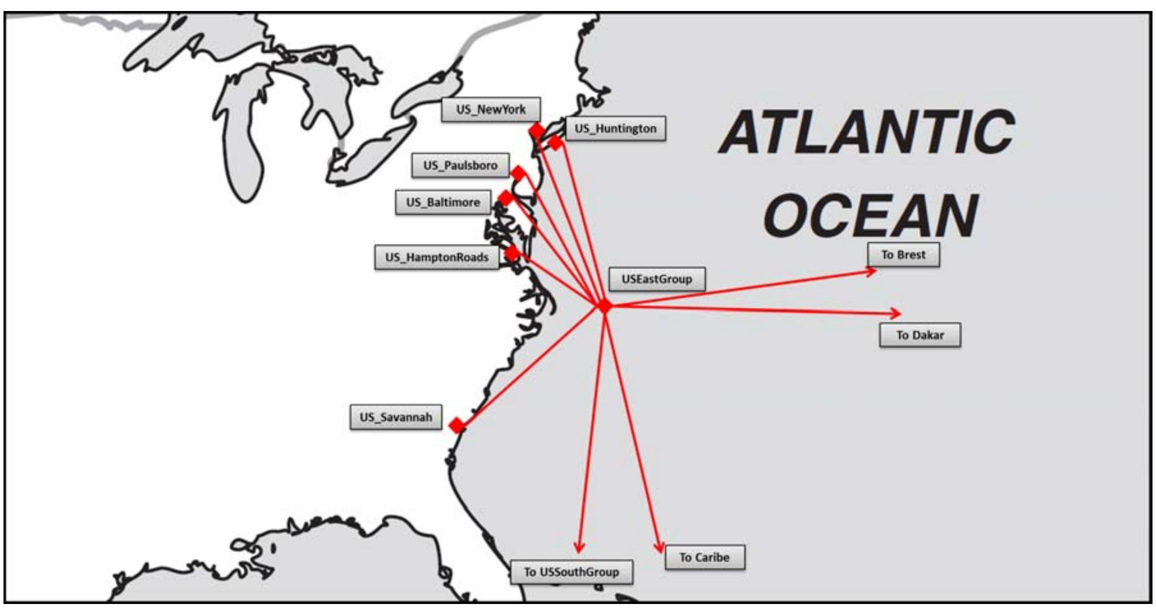

Figure 12. USSouth Group node

In areas where there are several small islands, an arc may traverse land (e.g., from Horn Island to Manila). We have ensured that these discrepancies compared to the actual sea routes are negligible.

The list of 416 arcs is shown in the Appendix, which contains a table with the distance between the origin and destination of each arc, expressed in n.m. and calculated using the same great-circle distance formula (5).

In addition to distance, another attribute associated with an arc is its capacity. This is the maximum amount of cargo that can be transported on the arc during a day. We consider that all arcs have infinite capacity, with the exception of the Panama Canal. According to research by the Panama Canal Authority (2012), its maximum capacity is between 280 to 290 million tons per year. This capacity includes cargo transported in both ways of circulation. In our model, we use half that capacity for each direction, which means 140-million tons annually or 384-thousand tons daily.

A general view of all arcs in the model is shown in Figure 13.

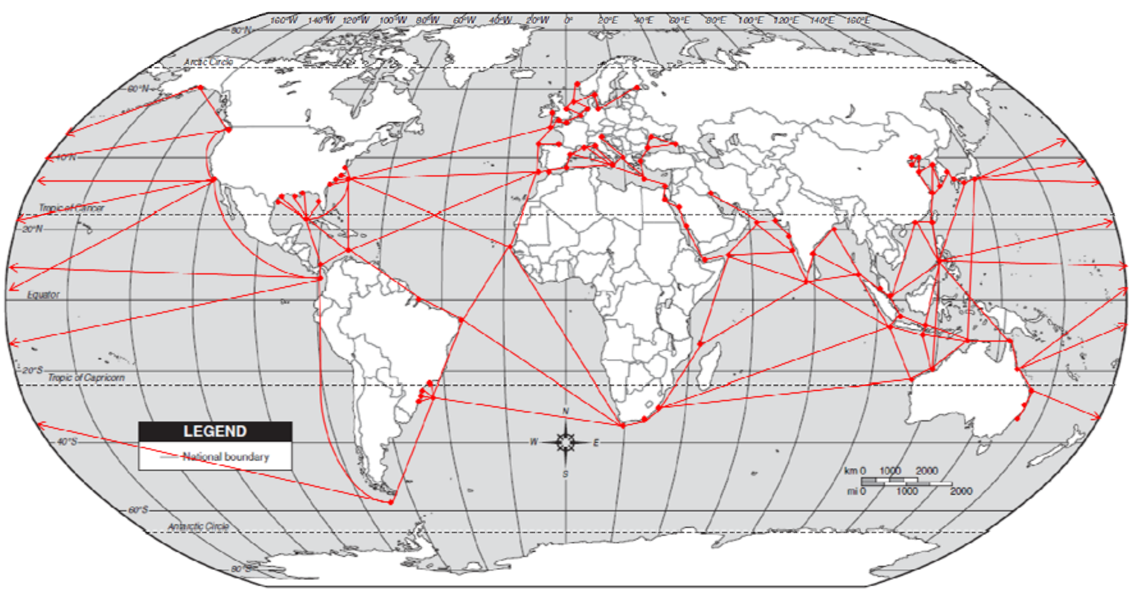

Figure 13. General view of all arcs in the model

D. INTERDICTION PENALTIES

Any arc that is subject to interdiction has a "penalty distance," which reflects the need to reroute ships in order to avoid the threat.

Notice that when an arc is interdicted, our model only considers the rerouting of the cargo through another available maritime route, which does not account for the potential use a different transportation means (truck, rail or air), or nearby port.

The criteria used to determine the penalty distance when an arc is interdicted depends on the geographical characteristics of the area. As a general rule, it is assumed that for longer arcs and arcs farther away from shore, the area of threat is bigger than for those that are short and close to shore. For this reason, their associated penalties (if interdicted) are longer. Some special cases, such as straits and canals, are analyzed independently.

In cases where an arc traverses open sea, it is assumed that the route must be deviated to avoid a zone that extends 400 n.m. beyond each side of the original arc's route. For the purpose of this work, it is assumed that the position of the threat is known. Assuming that the vessel begins deviation maneuvers 750 n.m. before the threat zone and recovers the original route 750 n.m. after the threat zone, a penalty of 200 n.m. is the additional distance that the vessel should travel to avoid the lateral 400 n.m. of the threat zone.

Figure 14 shows the original arc (dashed line) and the alternative, penalized route (solid line).

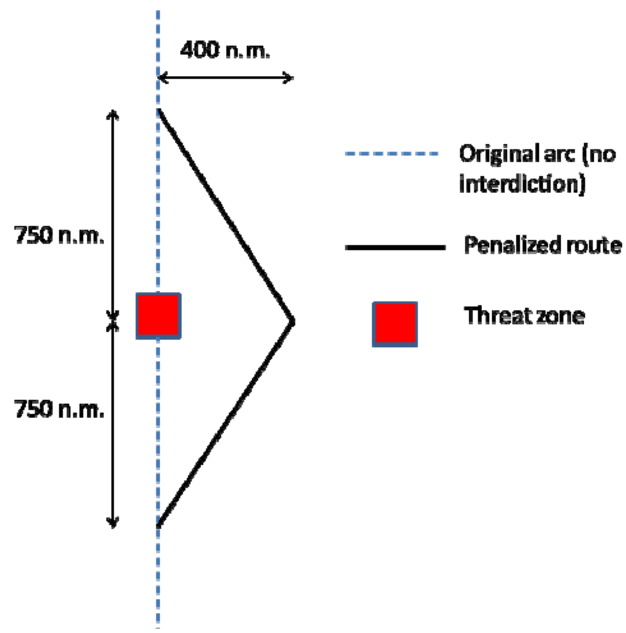

Figure 14. Deviation maneuvers in open sea

In the case of arcs with lengths of under 100 n.m., or when their distance from shore is no more than 50 n.m. (this usually occurs between ports of the same country) the additional distance used is 50 n.m., with the exception of straits and canals.

In the case of arcs between 100 and 300 n.m. long, the penalty is 100 n.m. (if those arcs do not use coastal routes). For arcs with a length between 300 and 1,500 n.m., the penalty is 150 n.m.

A special case is when the arc traverses a strait or canal: here, the penalty is assumed to be "infinite." This means that the arc and nearby routes will be closed, and other available routes (based solely on existing arcs) must be used. For the purpose of this work, the canals and straits considered under this situation are: Bab-el-Mandeb, Bosphorus, Gibraltar, Hormuz, Lombok, Malacca, Panama, Suez and Sunda.

The value of penalties for each arc is shown on the list of arcs in the Appendix. In our calculation, a penalty value equal to the sum of all arc lengths is used (instead of infinity) for straits and canals.

III. MULTI-COMMODITY NETWORK INTERDICTION MODEL

We model our maritime-transportation problem using a network with 155 nodes, of which 120 are ports and 35 are waypoints, with 416 arcs. It is assumed that we need to carry goods from every port to every other port. We tag each demand by port of origin, which we call "commodity." Thus, our defender's (operator's) problem is a capacitated, multi-commodity, minimum cost-flow model (Ahuja et al., 1993, pp. 294-344).

Our first goal is to estimate the minimum daily "transportation cost" of the global cargo shipment. Let us define this "cost" as the product of cargo volume carried (in tons) times the distance traveled by the cargo (in n.m.). We solve this problem under normal operating conditions, that is, in the absence of interdictions. Then, we develop an interdiction model of the flow in the network.

A. OPERATOR MODEL

The operator's problem is to route all cargo in the network in a manner that satisfies all supplies, demands, and capacities and incurs the lowest total transportation cost.

1. Mathematical Formulation

Let $G(I,A)$ be a directed network with node set I and arc set A. We use the following notation to formulate the operator model:

Indices and index sets:

I set of nodes, for $i, j \in I$

A set of arcs, for $(i, j) \in A$

C set of commodities, for $c \in C$. Note: One distinct commodity originates at every port node.

Data [units]:

t_{ij} distance from node i to node j [n.m.]

u_{ij} capacity of arc (i, j) [1000 × tons]

d_{ci} demand of commodity c at node i [1000 × tons]

s_{ci} supply of commodity c at node i [1000 × tons]. Note: Supply is zero, except for one commodity at each port node.

Decision variables [units]:

X_{cij} flow of commodity c on arc (i, j) [1000 × tons]

Operator model formulation:

$$\min_X \sum_c \sum_{(i,j)\in A} t_{ij} X_{cij} \qquad [6]$$

Subject to:

$$\sum_{j|(i,j)\in A} X_{cji} - \sum_{j|(i,j)\in A} X_{cij} = d_{ci} - s_{ci} \qquad \forall c, i \qquad [7a]$$

$$\sum_c X_{cij} \le u_{ij} \qquad \forall (i, j) \in A \qquad [7b]$$

$$X_{cij} \ge 0 \qquad \forall c, \forall (i, j) \in A \qquad [7c]$$

2. Discussion

The objective function (6) in the operator model calculates the total transportation cost. Constraint (7a) ensures balance of flow for all nodes and commodities. Constraint (7b) ensures that the flow on arc (*i, j*) does not exceed the capacity of arc (*i, j*). In our data, only the two directions of the Panama Canal have such a restriction (i.e., for all other arcs, $u_{ij} = \infty$). Finally, constraint (7c) ensures non-negative flow.

B. INTERDICTION MODEL

Let *n* be the number of arcs an attacker (or group of attackers) can interdict. We assume that each interdiction blocks the interdicted arc completely, so the full penalty discussed in Section II.D is applied to any traffic using the arc. Recall that this penalty reflects the additional distance required to travel around the arc, or an “infinite” penalty if that possibility does not exist. We also assume that, for any interdiction, both directions

of circulation are affected. Our AD model determines the set of n arcs to interdict that maximizes the resulting minimum flow cost in the network.

1. Mathematical Formulation

The AD model uses the following additional notation and formulation:

Data [units]:

p_{ij}	penalty for using interdicted arc (i, j) [n.m.]
n	number of interdictions [interdictions]

Decision variables [units]:

Y_{ij}	1 if arc (i, j) is interdicted, 0 otherwise [binary]
π_{ci}	dual of balance of flow for commodity c at node i [n.m.]
δ_{ij}	dual of capacity on arc (i, j) [n.m.]

AD model formulation (max-min):

$$\max_{Y} \min_{X} \sum_{c} \sum_{(i,j)\in A} (t_{ij} + p_{ij} Y_{ij}) X_{cij} \qquad [8]$$

Subject to: (Dual)

$$\sum_{j|(j,i)\in A} X_{cji} - \sum_{j|(i,j)\in A} X_{cij} = d_{ci} - s_{ci} \quad \forall c, i \qquad (\pi_{ci}) \qquad [9a]$$

$$\sum_{c} X_{cij} \le u_{ij} \quad \forall (i, j) \in A \qquad (\delta_{ij}) \qquad [9b]$$

$$X_{cij} \ge 0 \quad \forall c, \forall (i, j) \in A \qquad [9c]$$

$$\sum_{(i,j)\in A} Y_{ij} = 2n \qquad [9d]$$

$$Y_{ij} = Y_{ji} \quad \forall (i, j) \in A \,|\, i < j \qquad [9e]$$

$$Y_{ij} \in \{0,1\} \quad \forall (i, j) \in A \qquad [9f]$$

AD model formulation (max-max):

$$\max_{Y,\pi,\delta} \sum_{c} \sum_{i} (d_{ci} - s_{ci}) \pi_{ci} + \sum_{(i,j)\in A} u_{ij} \delta_{ij} \qquad [10]$$

Subject to:

$\pi_{cj} - \pi_{ci} + \delta_{ij} \leq (t_{ij} + p_{ij}Y_{ij}) \quad \forall c, \forall (i,j) \in A$ [11a]

$\delta_{ij} \leq 0 \quad \forall (i,j) \in A$ [11b]

π_{ci} unrestricted $\quad \forall c, i$ [11c]

(9d), (9e), (9f)

2. Discussion

The objective function (8) is similar to (6) in the operator model, with the exception that we introduce a penalty p_{ij} if the arc (*i*,*j*) is interdicted. Constraints (9a), (9b) and (9c) are the same as in the operator model.

Constraint (9d) ensures that *n* arcs are interdicted. Note that interdicting *n* arcs is modeled as 2*n* interdictions, because whenever arc (*i*,*j*) is interdicted, arc (*j*,*i*) must also be interdicted. Constraint (9e) ensures this is the case. Constraint (9f) ensures that interdictions are modeled as binary variables.

Because the objective of the attacker is to maximize the resulting minimum operator's cost, the max-min structure in (8) does not allow us to solve this AD model as a standard optimization problem. Thus, we take the dual of the inner minimization model, which results in the equivalent formulation (10) – (11c), in addition to constraints (9d), (9e), (9f) on the *Y* variables. The duals of constraints (9a) and (9b) become decision variables π_{ci} and δ_{ci} in the reformulation.

We may manually set an arc to be interdicted or non-interdictable (defended) by fixing the value of variable Y_{ij} to 1 or 0, respectively. This allows us to study the consequences of interdicting a pre-specified arc or group of arcs, or to model a scenario where an arc has been made invulnerable, e.g., by defending it using military vessels.

3. Implementation

This model has been implemented in the Generic Algebraic Modeling Software (GAMS, 2012).

A typical instance of our AD problem has approximately 19,400 decision variables of which 416 are binary (one for each interdictable arc), and 50,000 constraints. All of our instances (shown in the next chapter) solve in less than 10 seconds on a Hewlett Packard-Pavilion laptop with 4 GB of RAM at 2.27 GHz.

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IV. RESULTS AND ANALYSIS

A. BASELINE SCENARIO: GLOBAL SHIPMENT WITHOUT INTERDICTIONS

The first result that we obtain by running our operator model is the transportation cost of the total cargo shipment without interdictions; that is, the “normal” maritime traffic using the shortest routes (except as limited by arc capacities) with no threat. The transportation cost for this baseline scenario is 92.5 billions of ton-n.m. per day. This value does not represent the actual cost of the global maritime-cargo shipment, because our model considers only the 120 most important ports; however, it is useful as a reference when comparing the same network with interdictions.

In terms of monetary cost, assuming an average operating cost of $0.002 for the transport of one ton over one nautical mile, the daily cost of maritime transportation (considering only the movement of the 120 most important ports) would be $180.1 million.

Table 11 shows the daily flows (considering both ways of transportation) in the arcs at canals and straits considered as possible bottlenecks in our model.

Table 11. Baseline Scenario: Daily flows in the arcs for selected canals and straits

Arc (both directions)	Strait or canal	Flow (tons × 1000)
(Ma_TanjungPelepas, Si_Singapore)	Malacca	4,906
(Ma_Kelang, Ma_TanjungPelepas)	Malacca	4,773
(GibraltarW, Sp_Algeciras)	Gibraltar	4,035
(Sp_Algeciras, GibraltarE)	Gibraltar	4,028
(Sa_Jeddah, Aden)	Bab-el-Mandeb	3,914
(SuezN, SuezS)	Suez	3,829
(BosphorusN, BosphorusS)	Bosphorus	818
(PanamaW, PanamaE)	Panama	768
(SundaE, SundaW)	Sunda	585
(Sa_Jubail, Oman)	Hormuz	133
(LombokN, LombokS)	Lombok	29

The flow in the Panama Canal reaches its maximum capacity in both directions. According to our model, if the canal had no capacity limit, the daily flow in the Panama Canal would be 1,820 thousand tons.

Flows in Bosphorus, Sunda, Hormuz and Lombok straits are much lower than in the others straits or canals. However, as discussed below, they become important when considering scenarios with interdictions.

B. ONE-INTERDICTION SCENARIOS

In this section we present our analysis for cases where only one arc is interdicted, that is, n=1.

1. Scenario 1: Single Arc Interdiction and Arcs Not Defended

If we assume that any arc can be attacked, the optimal solution is an attack on the arc (BosphorusN, BosphorusS) in the Strait of Bosphorus. The reason for this solution (see Figure 6) is that by closing this strait, the ports of Constantza (Romania), Odessa (Ukraine), and Novorossisk (Russia) become isolated: all of them are on the coast of the Black Sea with no other way to ship their cargo by sea. Therefore, rather than an increase in distance traveled, this situation incurs unmet demand.

The Strait of Bosphorus is one of the arcs whose penalty is assumed to be infinite. In practice, the actual cost for this interdiction should be calculated by rerouting the cargo by train or truck to the nearest port outside the Black Sea, but such analysis is beyond the purpose of this thesis. If this strait is closed, a daily flow of 818 thousand tons (in both directions) would be interrupted.

The same consideration applies for the arc (Sa_Jubail, Oman) in the Strait of Hormuz (see Figure 8). In closing this strait, the port of Jubail (Saudi Arabia) becomes isolated, so a daily flow of 133 thousand tons (in both directions) remains interrupted.

In order to avoid these isolated instances, we set those arcs as defended (i.e., invulnerable), by fixing Y_{ij} to 0 for arcs (*i*,*j*) equal to (BosphorusN, BosphorusS) and (Sa_Jubail, Oman).

Running our AD model with the above provision, the optimal attack becomes (GibraltarW, Sp_Algeciras) in the Strait of Gibraltar. This interdiction causes a rerouting of the global shipment with a daily transportation cost of 115.3 billions of ton-n.m., which represents an increment of 24.65% with respect to the cost without interdictions. As we observe in Figures 6 and 10, in order to maintain the flow of cargo between the west and east sides of Gibraltar, that flow must be rerouted using available routes around the south of Africa. These new routes require traveling long distances that, in turn, incur a large increment in cost.

Assuming again an operating cost of $0.002 per ton-n.m., and considering only the 120 most important ports, the global maritime traffic cost when Gibraltar is closed would be $230.7 million. Thus, the additional daily cost due to rerouting would be $45.6 million.

2. Scenario 2: Single Arc Interdiction and Defended Arcs

Suppose that we allocate defense forces to protect the Strait of Gibraltar from interdiction. We wish to know which other interdicted arc would cause the next-worst disruption to our maritime flow. To analyze this situation, we set the arc (GibraltarW, Sp_Algeciras) as defended and run our interdiction model keeping n=1.

The solution for this case consist of an interdiction on the arc (Sp_Algeciras, GibraltarE), which also blocks any flow in the Strait of Gibraltar (see Figure 6). Therefore, we have almost the same result as in Scenario 1, except for the difference in flow that can arrive to (or leave from) the port of Algeciras (Spain) from the east and the west.

If we defend the two arcs in and out of the Strait of Gibraltar, the solution shows that the next arc to be interdicted is (Sa_Jeddah, Aden) in the Strait of Bab-el-Mandeb (also known as Mandab Strait*)*, connecting the Red Sea to the Gulf of Aden (see Figures 8 and 10). The total closure of this strait causes a rerouting of the global shipment resulting in a daily transportation cost of 110 billions of ton-n.m., which is an increment of 19.79% with respect to the cost without interdiction. As in the case of the Gibraltar Strait, a blockade of this strait also forces all cargo originally in the area to reroute around the south of Africa.

The economic cost when Bab-el-Mandeb Strait is closed would be $221.7 million and the additional daily cost due to rerouting would be $45.6 million.

Following this mechanism we obtain a ranking of the twelve most costly arc interdictions, provided that a single arc is attacked at a time. Table 12 shows the list of arc interdictions, along with the figures that show the arc location, daily transportation cost and relative increment of cost due to rerouting.

Table 12. Ranking of most costly single arc interdictions (excluding cases with isolated ports)

	Interdicted arc (*i*,*j*)	Fig.	Transportation cost (billions of ton-n.m.)	Relative increment (%)
0	No interdictions	-	92.5	-
1	(GibraltarW, Sp_Algeciras)	6, 10	115.3	24.65
2	(Sp_Algeciras, GibraltarE)	6,10	114.9	24.19
3	(Sa_Jeddah, Aden)	8, 10	110.8	19.79
4	(SuezN, SuezS)	8, 10	109.8	18.70
5	(PanamaW, PanamaE)	4, 5	99.6	7.66
6	(Ma_TanjungPelepas, Si_Singapore)	7	98.0	5.96
7	(Ma_Kelang, Ma_TanjungPelepas)	7	97.6	5.53
8	(Socotra, SriLanka)	8	93.2	0.75
9	(Ma_Kelang, BandaAceh)	7	93.2	0.75
10	(SriLanka, BandaAceh)	7, 8	93.2	0.67
11	(Aden, Socotra)	8	93.1	0.63
12	(SuezS, Sa_Yanbu)	8	93.1	0.62

In Figure 15, we observe a comparative chart of the relative cost increment due to rerouting for the twelve most costly single-arc interdictions. For better understanding, we have replaced the names of actual arcs with the names of the geographical areas where the arcs are located.

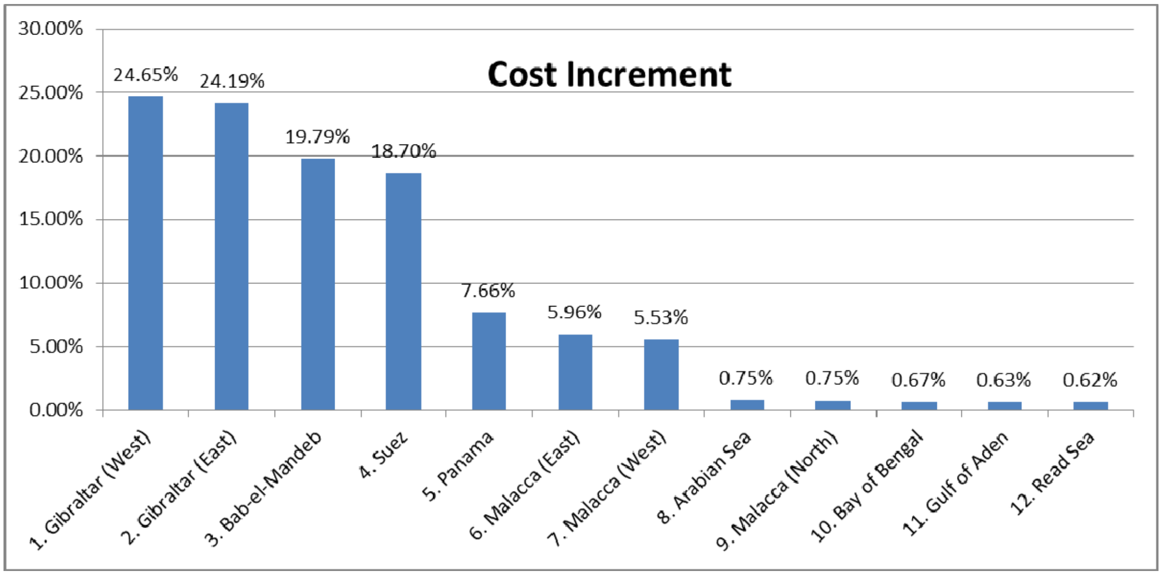

Figure 15. Relative cost increment due to rerouting for the twelve most costly single-arc interdictions (excluding cases with isolated ports)

After the interdictions of the Strait of Gibraltar and the Strait of Bab-el-Mandeb, the next-worst interdiction corresponds to the arc (SuezN, SuezS) in the Suez Canal, connecting the Mediterranean Sea to the Red Sea, causing a relative cost increment of 18.70%. The cause of this increment is, again, an increase in the traveled distance.

The next worst-case interdiction is the arc (PanamaW, PanamaE) in the Panama Canal, causing a cost increment of 7.66%, which is significantly lower than in the previous cases. Despite the long rerouting needed around the south of South America, the amount of cargo involved is not as important as in the above cases, because the flow through the Panama Canal under normal conditions is relatively low due to its limited capacity.

The next two single interdictions in the ranking correspond to the arcs (Ma_TanjungPelepas, Si_Singapore) and (Ma_Kelang, Ma_TanjungPelepas) in the Malacca Strait, with cost increments of 5.96% and 5.53%, respectively. In these cases, the cost increment is due to the large amount of cargo to be rerouted, rather than the length of the new route. In fact, the flows on those arcs are the highest (see Table 11); thus, a relatively short rerouting using arcs surrounding the Sumatra Island causes a large cost increase.

The rest of the interdictions in the chart show a lower impact on global traffic, with cost increments below 1%. Note that, unlike previous interdictions, an attack on those arcs does not imply a total closure of the arc, but a certain penalty length (i.e., 50, 100, 150 or 200 n.m.).

Interdicted arcs in dashed, thicker line (except in the Panama Canal and Strait of Gibraltar) are shown in Figures 16 and 17. Figure 18 shows each interdicted arc with a label indicating its position in the ranking.

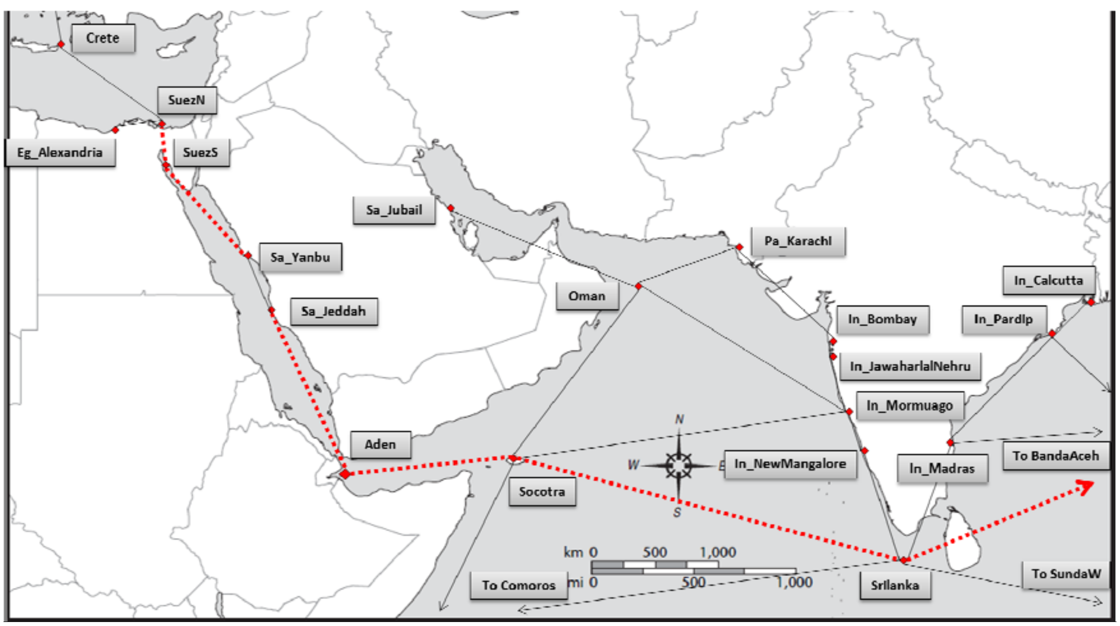

Figure 16. Scenario 2: Detailed view of interdicted arcs in Central and Southwest Asia

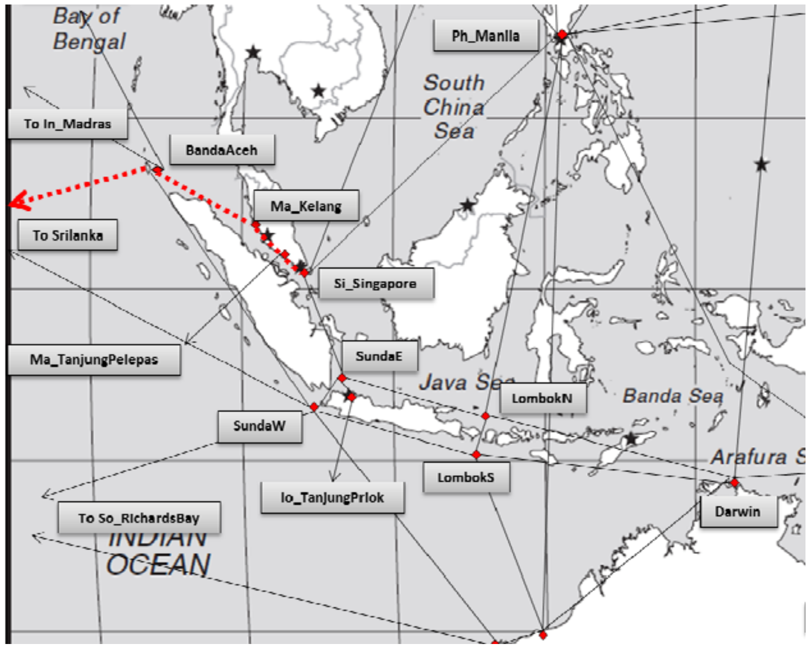

Figure 17. Scenario 2: Detailed view of interdicted arcs in Southeast Asia

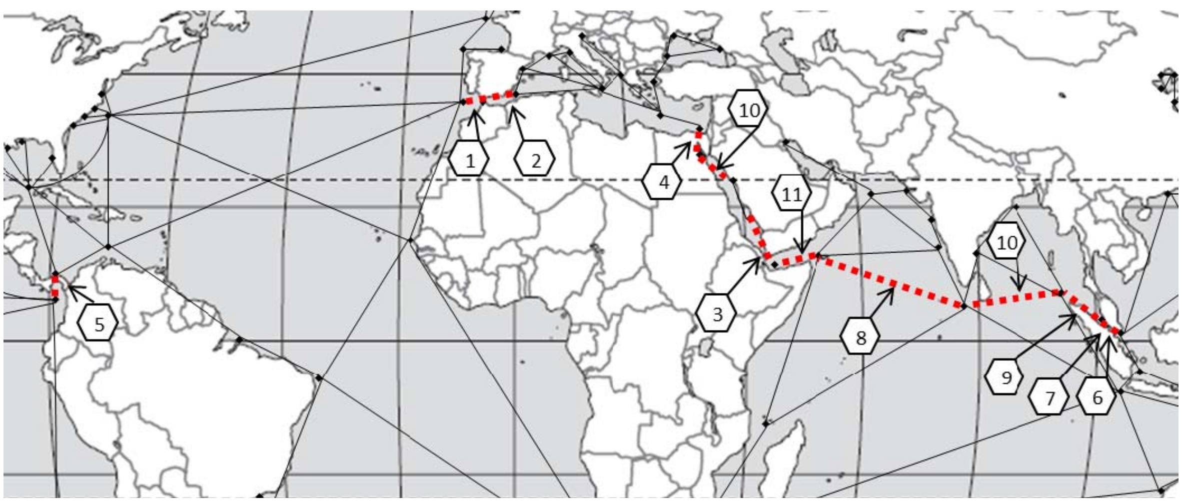

Figure 18. Scenarios 1 and 2: All interdicted arcs with ranking position indication (excluding cases with isolated ports)

C. MULTIPLE INTERDICTION SCENARIOS

In this section we analyze scenarios where two or three simultaneous interdictions are possible.

1. Scenario 3: Two-Arc Interdiction and Arcs Not Defended

We first assume *n*=2 and any arc can be attacked. The optimal solution for this scenario is an attack on the arcs (GibraltarW, Sp_Algeciras) and (Sa_Jeddah, Aden). Closure of the Strait of Gibraltar and the Strait of Bab-el-Mandeb causes the isolation of all the ports in the Mediterranean Sea and Red Sea from the rest of the ports (see Figures 6, 8 and 10). This case, similar to the closure of the Straits of Bosphorus and Hormuz explained above, is a case of unmet demand, because there are no alternative routes to trade outside the isolated area. Therefore, rerouting costs associated with this interdiction are not analyzed.

Table 13 shows the pair of arcs whose simultaneous interdiction causes the isolation of one or more ports.

Table 13. Scenario 3: Pairs of arcs whose simultaneous interdiction causes the isolation of one or more ports

Pair of interdicted arcs	Isolated ports
(GibraltarW, Sp_Algeciras) and (Sa_Jeddah, Aden)	Ports in Mediterranean Sea and Red Sea
(GibraltarW, Sp_Algeciras) and (SuezN, SuezS)	Ports in Mediterranean Sea
(SuezN, SuezS) and (Sa_Jeddah, Aden)	Ports in Red Sea
(GibraltarW, Sp_Algeciras) and (Sp_Algeciras, GibraltarE)	Port of Algeciras (Spain)
(Ma_Kelang, Ma_TanjungPelepas) and (Ma_TanjungPelepas, Si_Singapore)	Port of Tanjung Pelepas (Malaysia)

Assuming that no isolation interdictions will take place, the optimal solution for two simultaneous interdictions is an attack on arcs (GibraltarW, Sp_Algeciras) in the Mediterranean Sea and (PanamaW, PanamaE) in the Panama Canal. The rerouting derived from this attack would cause a daily transportation cost of 123.3 billions of ton-n.m., which implies an increment of 33.22% with respect to the cost without interdictions. The monetary daily cost of these interdictions would be $246.5 million, and the additional daily cost due to rerouting would be $61.5 million.

The second-worst simultaneous interdiction corresponds to arcs (GibraltarW, Sp_Algeciras) and (Ma_TanjungPelepas, Si_Singapore) in the Strait of Malacca. These interdictions would cause a daily transportation cost of 118.8 billions of ton-n.m., that is, an increment of 28.44% with respect to the cost without interdictions. The monetary daily cost of these attacks would be $237.7 million, and the additional daily cost due to rerouting would be $52.6 million.

Other near-optimal simultaneous interdictions would correspond to arcs (Sa_Jeddah, Aden) and (PanamaW, PanamaE), with an increment of 28.35%, and (SuezN, SuezS) and (PanamaW, PanamaE), with an increment of 27.27%.

The relative cost increments for these paired interdictions are shown in Figure 19.

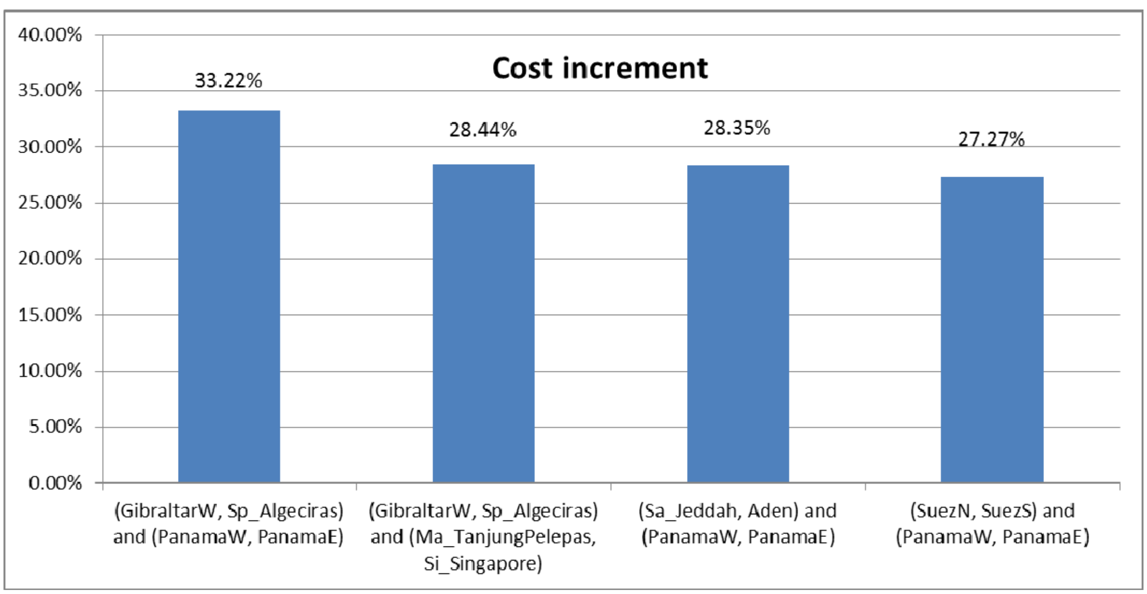

Figure 19. Scenario 3: Relative cost increment for two simultaneous interdictions (excluding cases with isolated ports)

2. Scenario 4: Two-Arc Interdiction and Defended Arcs in Gibraltar, Suez and Panama

Perhaps a more realistic scenario would consist of assuming the arcs in the Strait of Gibraltar, Suez Canal and Panama Canal are well-defended. Table 14 shows a list of the alternative *n*=2 interdictions, along with the daily transportation cost, and the relative cost increment due to rerouting.

Table 14. Scenario 4: Pairs of interdictions, assuming Strait of Gibraltar, Suez Canal and Panama Canal are defended

	Pair of interdicted arcs	Transportation cost (billions of ton-n.m.)	Relative cost increment (%)
0	No interdictions	92.5	-
1	(Sa_Jeddah, Aden) and (Ma_TanjungPelepas, Si_Singapore)	113.3	22.54
2	(Sa_Jeddah, Aden) and (Dakar, So_SaldanhaBay)	111.6	20.60
3	(Sa_Jeddah, Aden) and (GibraltarW, Dakar)	111.4	20.44
4	(Sa_Jeddah, Aden) and (SundaW, SundaE)	111.4	20.38
5	(Sa_Jeddah, Aden) and (Si_Singapore, SundaE)	111.3	20.32
6	(Sa_Jeddah, Aden) and (RichardsBay, SundaW)	111.3	20.25

The optimal solution for this scenario is the simultaneous interdiction of the arcs (Sa_Jeddah, Aden) and (Ma_TanjungPelepas, Si_Singapore) located in the Strait of Bab el Mandeb and the Strait of Malacca, respectively.

Other pairs of interdictions in this ranking include: the arc in the Strait of Bab el Mandeb and the arcs (Dakar, So_SaldanhaBay) and (GibraltarW, Dakar) on the west coast of Africa; and the arc (RichardsBay, SundaW) on the east of Africa. These arcs around Africa increase considerably in flow if some of the arcs in the Strait of Gibraltar, Suez Canal or the Strait of Bab el Mandeb are closed, because they take most of the flow that normally traverses the Mediterranean Sea and the Red Sea. For this reason, they also become attractive targets.

Figure 20 shows a comparative chart of the relative cost increment due to rerouting for the six most costly arc interdictions in this scenario.

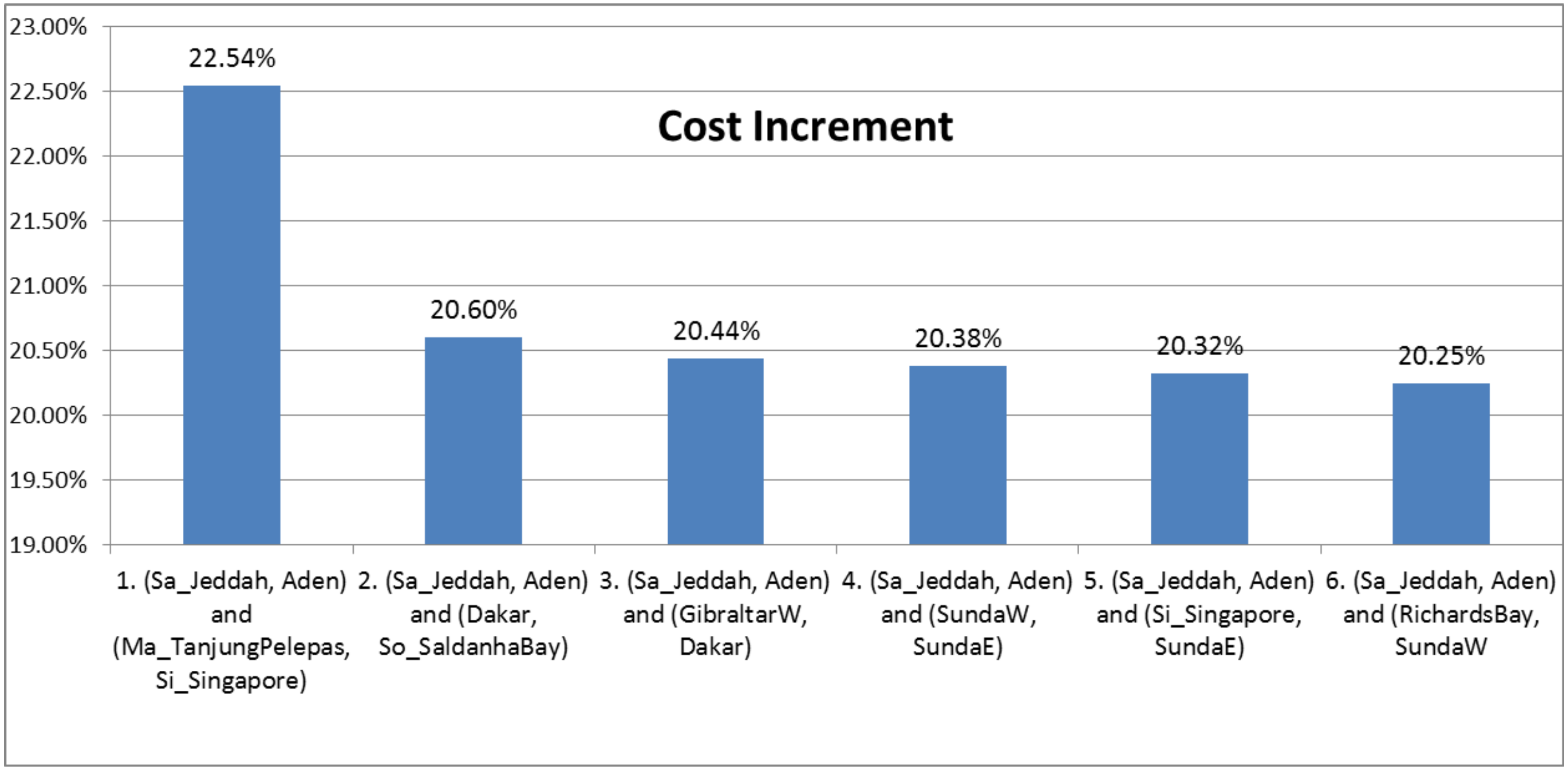

Figure 20. Scenario 4: Relative cost increment due to rerouting for the six most costly two-arc interdictions assuming Strait of Gibraltar, Suez Canal and Panama Canal are defended

The Strait of Bab el Mandeb becomes the most critical region in this scenario because it is present in every pair of arc interdictions. The arcs around Africa are also important because of their increasing flow. Other arcs playing an important role in this scenario are those in the Strait of Malacca and the Strait of Sunda, located around the Indonesian island of Sumatra.

3. Scenario 5: Two-Arc Interdiction and Defended Arcs in Gibraltar, Suez, Panama and Bab el Mandeb

Let us analyze a new scenario in which we assume that, besides the Strait of Gibraltar, Suez Canal, and Panama Canal, the Strait of Bab el Mandeb is also well-defended. We maintain *n*=2 interdictions. With these assumptions, interdictions will focus on the arcs in the Southeast of Asia region.

The optimal solution for this scenario is a simultaneous attack on the arcs (Ma_TanjungPelepas, Si_Singapore) and (SundaW, SundaE) in the straits of Malacca and Sunda, which cause a relative cost increment of 8.27%. The next most costly arc interdictions are shown in Table 15.

Table 15. Scenario 5: Pairs of interdictions, assuming the Strait of Gibraltar, Suez Canal and Panama Canal and Strait of Bab el Mandeb are defended

	Pair of interdicted arcs	Transportation cost (billions of ton-n.m.)	Relative cost increment (%)
0	No interdictions	92.5	-
1	(Ma_TanjungPelepas, Si_Singapore) and (SundaW, SundaE)	100.2	8.27
2	(Ma_TanjungPelepas, Si_Singapore) and (SriLanka, SundaW)	98.9	6.89
3	(Ma_TanjungPelepas, Si_Singapore) and (Si_Singapore, SundaE)	98.9	6.88
4	(Ma_TanjungPelepas, Si_Singapore) and (Socotra, SriLanka)	98.7	6.71

5	(Ma_TanjungPelepas, Si_Singapore) and (Aden, Socotra)	98.6	6.59
6	(Ma_TanjungPelepas, Si_Singapore) and (SuezS, Sa_Yanbu)	98.6	6.58

Figures 21 and Figure 22 show the interdicted arcs in dashed, thicker line. Note that the Strait of Malacca is present in every pair of interdictions. This is an indicator of the importance of this strait.

Figure 23, shows the relative cost increments, due to rerouting, for the six most costly arc interdictions in this scenario.

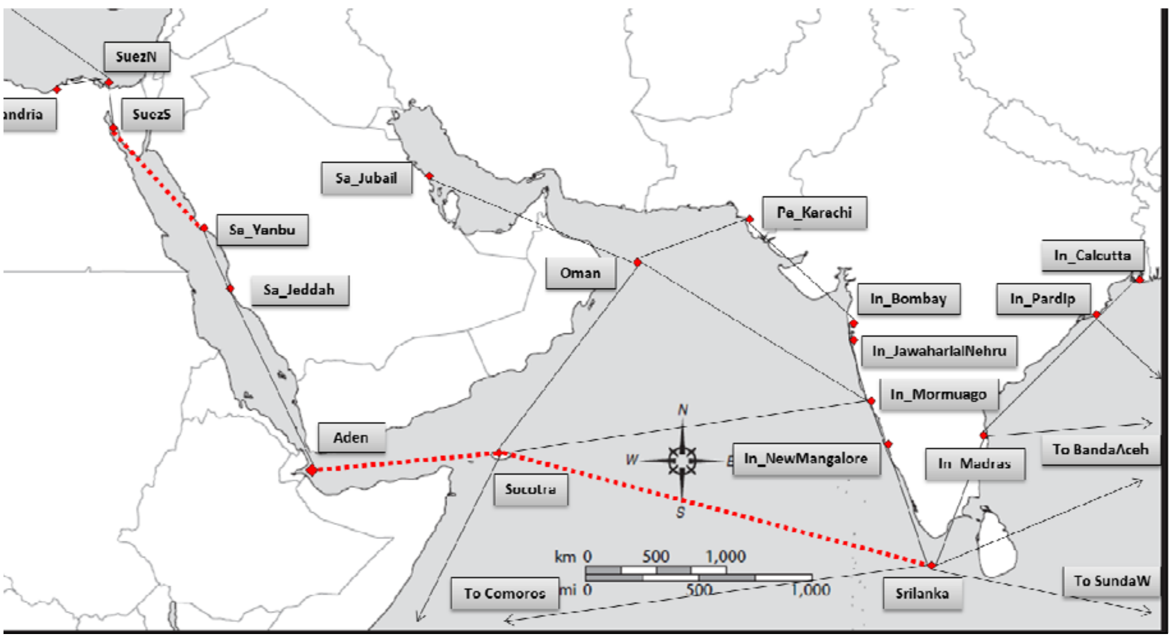

Figure 21. Scenario 5: Two-arc interdictions in Central and Southwest Asia

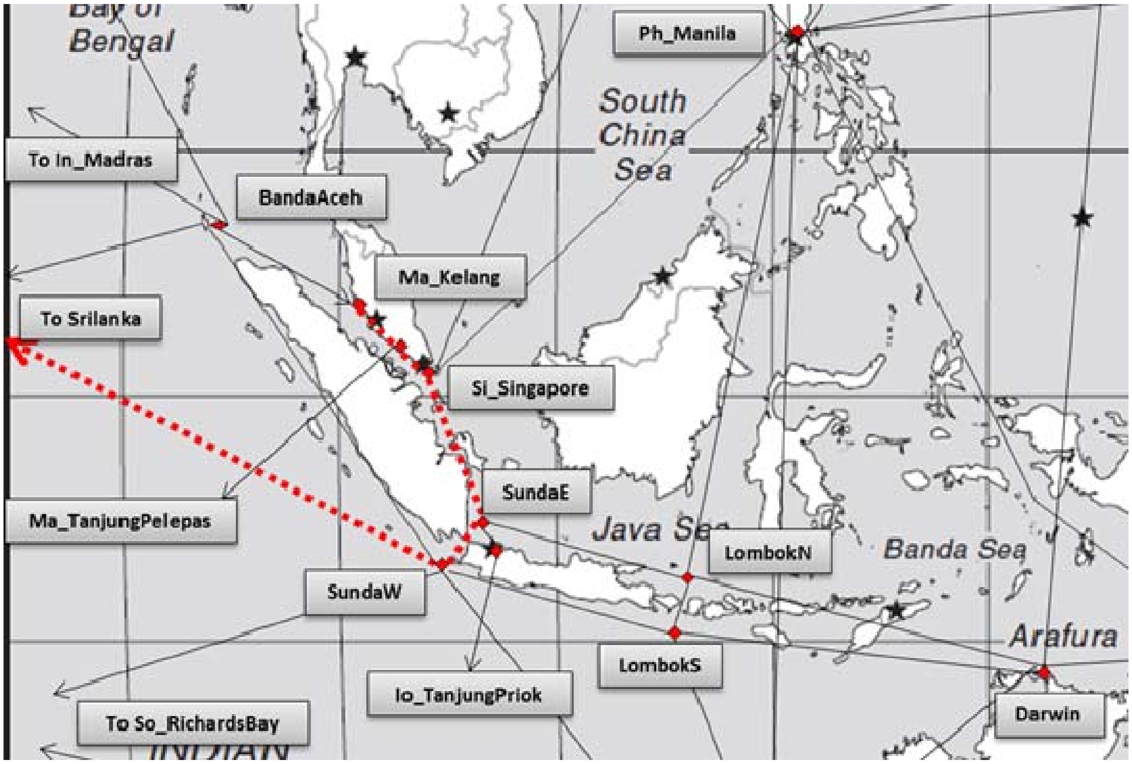

Figure 22. Scenario 5: Two-arc interdictions in Southeast Asia

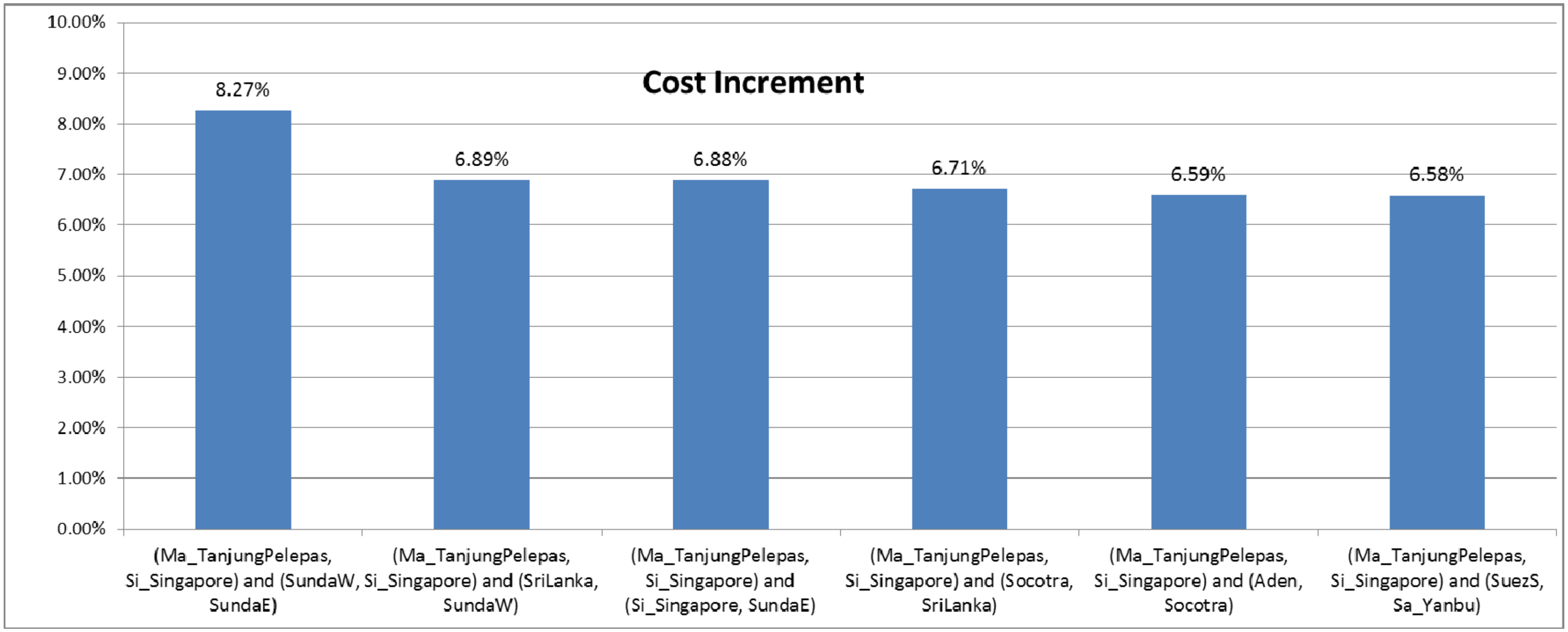

Figure 23. Scenario 5: Relative cost increment for two-arc interdictions

4. Scenario 6: Three-Arc Interdiction and Defended Arcs in Gibraltar, Suez, Panama and Bab el Mandeb

For this scenario, the arcs in the straits of Gibraltar and Bab el Mandeb, and canals of Panama and Suez remain well defended, but now three interdictions are allowed (n=3). The optimal solution given by our AD model shows optimal interdictions at (Ma_TanjungPelepas, Si_Singapore), (SundaW, SundaE) and (LombokN, LombokS), in the straits of Malacca, Sunda and Lombok, respectively (see Figure 24). All these straits are controlled by only one country, and their closure has the effect of a barrier along Sumatra Island, Java Island, and the group of small islands east of Java.

If these arcs are interdicted, the daily transportation cost would be 106.9 billions of ton-n.m., meaning an increment of 15.54% with respect to the cost without interdictions. The daily monetary cost would be $213.8 million and the additional daily cost due to rerouting would be $28.7 million.

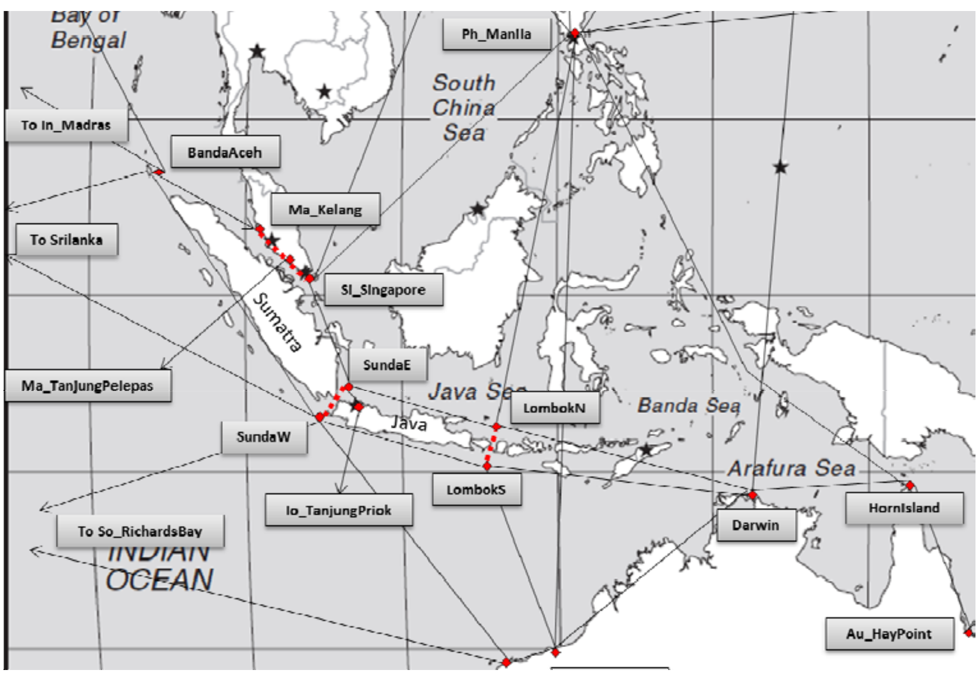

Figure 24. Scenario 6: Interdicted arcs assuming three interdictions and the straits of Gibraltar and Bab el Mandeb, and canals of Panama and Suez defended

5. Scenario 7: Two-arc and three-arc interdiction and defended arcs in Gibraltar, Suez, Panama, Bab el Mandeb, and Malacca

Let us consider a final scenario where we add another defense in the Strait of Malacca, in addition to the defenses in Scenarios 5 and 6.

The optimal solution for two-arc interdictions (n=2) corresponds to the arcs (Socotra, SriLanka) and (BandaAceh, Ma_Kelang) with a daily transportation cost of 93.9 billions of ton-n.m., which represents an increment of 1.5% with respect to the cost without interdictions. This is significantly lower than the 8.27% cost increase of Scenario 5, where the Strait of Malaca is not included in the set of defenses.

In case that three-arc interdictions are allowed (n=3), the arcs (Socotra, SriLanka), (SriLanka, BandaAceh) and (BandaAceh, Ma_Kelang) become the optimal solution, with a daily transportation cost of 94.5 billions of ton-n.m., and a cost increment of 2.17%. Again, this significantly reduces the 15.54% cost increase of Scenario 6.

For two-arc interdictions, the daily monetary costs would be $187.8 million and the additional daily cost due to rerouting would be $2.8 million. The corresponding costs for three-arc interdictions would be $189.1 billion and $4.0 billion respectively.

6. Summary Comparisons

Figure 25 compares the relative cost increments corresponding to the closure of the Strait of Malacca only, the closure of the straits of Malacca and Sunda and the closure of the straits of Malacca, Sunda and Lombok, along with the single interdiction of the Straits of Gibraltar and Bab el Mandeb and the canals of Suez and Panama.

The action of a triple simultaneous attack notably increases the cost of maritime transport which is higher than the increment caused by the closure of the Panama Canal and slightly lower than the increments caused by the closure of the Strait of Bab el Mandeb or Suez Canal.

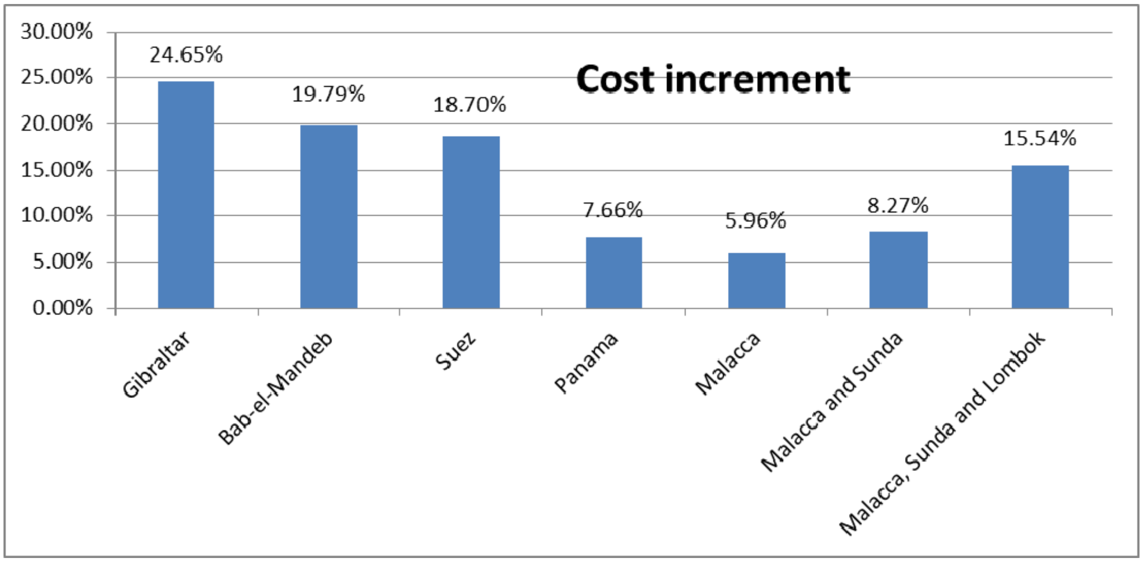

Figure 25. Comparative chart of cost increment caused by interdictions in Gibraltar; Bab el Mandeb; Suez; Panama; Malacca; Malacca and Sunda; and Malacca, Sunda, and Lombok.

Figure 26, shows the relative cost increment for one-arc and two-arc optimal interdictions, for the following defended arcs: Gibraltar; Gibraltar and Bab el Mandeb; Gibraltar, Bab el Mandeb and Suez; Gibraltar, Bab el Mandeb, Suez and Panama; and Gibraltar, Bab el Mandeb, Suez, Panama and Malacca.

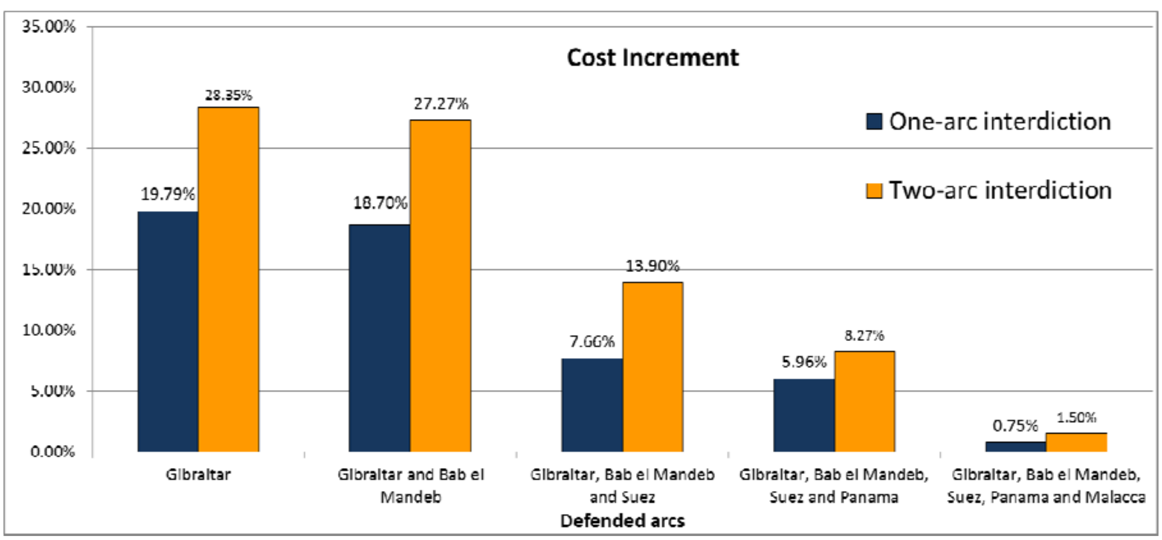

Figure 26. Cost increment for one-arc interdiction and two-arc interdiction, for several sets of defended arcs

A notable reduction in cost increment is observed when the five straits and canals are defended.

The associated optimal solution (interdicted arcs) for every set of defenses in Figure 26 is shown in Table 16.

Table 16. Interdicted arcs for every set of defended straits and canals

Defended strait/canal	Interdicted arcs (One-arc interdiction)	Interdicted arcs (Two-arc interdictions)
Gibraltar	(Sa_Jeddah, Aden)	(Sa_Jeddah, Aden) and (PanamaE, PanamaW)
Gibraltar and Bab el Mandeb	(SuezN, SuezS)	(SuezN, SuezS) and (PanamaE, PanamaW)
Gibraltar, Bab el Mandeb and Suez	(PanamaE, PanamaW)	(PanamaE, PanamaW) and (Ma_TanjungPelepas, Si_Singapore)
Gibraltar, Bab el Mandeb, Suez and Panama	(Ma_TanjungPelepas, Si_Singapore)	(Ma_TanjungPelepas, Si_Singapore) and (SundaE, SundaW)
Gibraltar, Bab el Mandeb, Suez, Panama and Malacca	(Socotra, SriLanka)	(Socotra, SriLanka) and (BandaAceh, Ma_Kelang)

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V. CONCLUSIONS AND FUTURE RESEARCH

A. CONCLUSIONS

We have built a maritime network model to approximate sea routes for worldwide transportation of commodities. We propose an AD model to identify geographical points at sea whose interdiction may cause the largest deviation of cargo flow from the original routes.

The network contains 120 nodes representing the 120 most important ports in the world (based on volume of cargo), 35 waypoint nodes at sea, and 416 arcs to interconnect all the ports. The interdiction of an arc incurs a penalty equivalent to the additional distance that we estimate ships would need to travel in order to avoid the threat. In cases of straits and canals we assume a total blockade of the sea lane, forcing the model to seek alternative routes of transportation.

The information to populate the model has been obtained from different sources. Unfortunately, we have not found precise information for supply and demand at every port. Instead, we have used:

(a) total volume handled by the port,

(b) trade balance of the country where the port is located,

(c) import and export rates between pairs of countries, and

(d) a gravity model,

as surrogates for estimating:

(i) the total supply available from each port (which is defined as a distinct commodity), and

(ii) the demand of each commodity at each port.

By running our AD model, we analyze several scenarios that vary depending on the set of arcs we assume are defended and the number of simultaneous interdictions

allowed for the attacker. For every scenario we elaborate a ranking of the worst-case interdictions, identify the interdicted arcs, and calculate their costs, measured in ton-n.m.

Excluding interdictions that cause the isolation of a port, we find that the interdiction (and closure) of the Strait of Gibraltar alone generates the largest disruption with a cost increase of 24.65% with respect to the non-interdicted network. We identify other important isolated attacks in the Strait of Bab el Mandeb (cost increase of 19.79%), Suez Canal (18.70%), Panama Canal (7.66%), and Strait of Malacca (5.96%). In some of these cases, the interdiction is explained by the increase in distance the cargo would need to travel, whereas in other cases the predominant factor is the amount of cargo involved.

For two simultaneous interdictions we discover several cases which would also isolate regions from any maritime transportation. Excluding those cases, we observe that the interdiction of the Panama Canal and the Strait of Gibraltar produce the largest cost increment of 33.22%. When the Panama and Suez canals, and the Strait of Gibraltar are assumed to be defended, the optimal interdictions become the Strait of Bab el Mandeb and the Strait of Malacca, with a cost increase of 22.54%.

Assuming all the arcs in Gibraltar, Panama, Suez and Bab el Mandeb are defended, the optimal simultaneous attack on two arcs involves the arcs of the straits of Malacca and Sunda, with a cost increase of 8.27%. This value can still be considered relatively large given that is calculated assuming four critical regions are already defended. In fact, we provide a ranking of the six most costly pairs of interdictions under these conditions, and all of them contain the Strait of Malacca. Furthermore, if we allow three interdictions, an attack on the arcs in the straits of Malacca, Sunda and Lombok yields a cost increment of 15.54%.

Fortunately, these worst-case scenarios of attack improve if we add an additional defense in the Strait of Malacca: the cost increment decreases from 8.27% to 1.5% for two interdictions, and from 15.54% to 2.17% for three interdictions.

All analysis reported in this thesis can be independently repeated using the data given here.

B. RECOMMENDATIONS FOR FUTURE RESEARCH

Future research may use the existing model to analyze other non-piracy scenarios, such as the denial of an entire area by a country.

Even though we use the 120 most important ports, a more accurate result could be achieved by considering many other smaller ports around the world. In addition, more accurate supply and demand information could be obtained, for example, from maritime insurance companies like Lloyd's.

The model can also be improved by adding more realistic features, such as different types of vessels (by size, tonnage, country of registration, etc.) and cargo (oil, grains, containerized cargo, bulk cargo, etc.). Then, some routes could be restricted for certain vessel sizes or types of cargo.

The analysis can also be enhanced by allowing a multi-modal transportation network (including air, train and truck), so the cost of transporting the cargo by other means could be compared with the cost of rerouting the cargo by sea. This is especially important when a sea route is completely blocked, as in the case of straits or canals, and when ports become isolated.

The models presented here scale up and there is no telltale that these embellishments would prove excessively difficult to solve.

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APPENDIX

This appendix contains the list of 416 arcs used in our model of global maritime network. We include the length of the arc and the penalty distance if the arc is interdicted. Note: For arcs with “infinite” penalty (complete blockage), our implementation uses a penalty equal to the sum of all of the arc lengths.

From	To	Length (n.m.)	Penalty (n.m.)
Au_Hedland	Au_Dampier	123.25	50
Au_Hedland	Ph_Manila	2417.66	200
Au_Hedland	Darwin	1073.89	150
Au_Hedland	LombokS	779.93	150
Au_Dampier	Au_Hedland	123.25	50
Au_Dampier	SundaW	1263.72	150
Au_Dampier	So_RichardsBay	5234.11	200
Au_Newcastle	Au_Brisbane	384.20	50
Au_HayPoint	Au_Gladstone	216.07	50
Au_HayPoint	Us_LosAngeles	7164.14	200
Au_HayPoint	HornIsland	899.58	50
Au_HayPoint	PanamaW	8789.93	200
Au_Gladstone	Au_Brisbane	273.20	50
Au_Gladstone	Au_HayPoint	216.07	50
Au_Gladstone	Magellan	6395.54	200
Au_Brisbane	Au_Newcastle	384.20	50
Au_Brisbane	Au_Gladstone	273.20	50
Be_Antwerp	Be_Zeebrugge	52.50	50
Be_Antwerp	Ne_Rotterdam	48.83	50
Be_Antwerp	Uk_Grimsby	255.38	50

From	To	Length (n.m.)	Penalty (n.m.)
Be_Zeebrugge	Be_Antwerp	52.50	50
Be_Zeebrugge	Fr_Dunkirk	41.20	50
Br_Itaqui	Natal	2207.13	50
Br_Itaqui	Caribe	3202.55	50
Br_Tubarao	BrazilGroup	507.10	50
Br_Sepetiba	BrazilGroup	199.08	50
Br_Santos	BrazilGroup	305.12	50
Br_SaoSebastiao	BrazilGroup	255.11	50
Br_Paranagua	BrazilGroup	428.35	50
Br_AngradosReis	BrazilGroup	224.23	50
Ca_Vancouver	Us_LosAngeles	1079.90	50
Ca_Vancouver	Us_Valdez	1217.69	50
Ca_Vancouver	Ja_Yokohama	4708.13	200
Ch_Qingdao	Ch_Rizhao	65.76	50
Ch_Qingdao	Ch_Yantai	113.09	50
Ch_Qinhuangdao	Ch_Dalian	128.59	50
Ch_Shanghai	Ch_Ningbo	94.20	50
Ch_Shanghai	Ch_Nantong	62.02	50
Ch_Shanghai	Ch_Lianyungang	266.74	50
Ch_Shanghai	Ch_Taichung	484.55	50
Ch_Shanghai	Ko_Inchon	523.34	50
Ch_Shanghai	Jeju	348.39	150
Ch_Tianjin	Ch_Dalian	237.27	50
Ch_Ningbo	Ch_Shanghai	94.20	50
Ch_Guangzhou	Ch_Shenzhen	64.75	50
Ch_HongKong	Ch_Shenzhen	10.66	50
Ch_HongKong	Ch_Kaohsiung	420.02	50

From	To	Length (n.m.)	Penalty (n.m.)
Ch_HongKong	Ph_Manila	701.91	150
Ch_HongKong	Si_Singapore	1609.96	200
Ch_Dalian	Ch_Qinhuangdao	128.59	50
Ch_Dalian	Ch_Tianjin	237.27	50
Ch_Dalian	Ch_Yingkou	125.52	50
Ch_Dalian	Ch_Yantai	100.61	50
Ch_Dalian	Ch_Tangshan	190.23	50
Ch_Shenzhen	Ch_Guangzhou	64.75	50
Ch_Shenzhen	Ch_HongKong	10.66	50
Ch_Rizhao	Ch_Qingdao	65.76	50
Ch_Rizhao	Ch_Lianyungang	59.23	50
Ch_Yingkou	Ch_Dalian	125.52	50
Ch_Nantong	Ch_Shanghai	62.02	50
Ch_Nantong	Ch_Nanjing	122.99	50
Ch_Yantai	Ch_Qingdao	113.09	50
Ch_Yantai	Ch_Dalian	100.61	50
Ch_Yantai	Ko_Inchon	288.30	100
Ch_Yantai	Jeju	381.23	150
Ch_Nanjing	Ch_Nantong	122.99	50
Ch_Tangshan	Ch_Dalian	190.23	50
Ch_Lianyungang	Ch_Shanghai	266.74	50
Ch_Lianyungang	Ch_Rizhao	59.23	50
Ch_Lianyungang	Jeju	423.69	150
Ch_Kaohsiung	Ch_HongKong	420.02	50
Ch_Kaohsiung	Ch_Taichung	86.24	50
Ch_Kaohsiung	Ph_Manila	581.54	150
Ch_Taichung	Ch_Shanghai	484.55	50

From	To	Length (n.m.)	Penalty (n.m.)
Ch_Taichung	Ch_Kaohsiung	86.24	50
Eg_Alexandria	SuezN	149.14	100
Fr_Marseilles	It_Leghorn	248.40	50
Fr_Marseilles	Sp_Barcelona	209.96	50
Fr_Marseilles	Messina	645.97	150
Fr_LeHavre	Fr_Calais	126.97	50
Fr_LeHavre	Uk_Southampton	118.47	100
Fr_Dunkirk	Be_Zeebrugge	41.20	50
Fr_Dunkirk	Fr_Calais	23.19	50
Fr_Dunkirk	Uk_London	113.04	100
Fr_Calais	Fr_LeHavre	126.97	50
Fr_Calais	Fr_Dunkirk	23.19	50
Ge_Hamburg	Ge_Bremen	57.93	50
Ge_Bremen	Ge_Hamburg	57.93	50
Ge_Bremen	Ge_Wilhelmshaven	19.60	50
Ge_Wilhelmshaven	Ge_Bremen	19.60	50
Ge_Wilhelmshaven	Ne_Amsterdam	153.08	50
Ge_Wilhelmshaven	Uk_Grimsby	341.31	150
Ge_Wilhelmshaven	NorthSea	245.97	100
Ge_Lubeck	Ru_Primorsk	804.30	150
Ge_Lubeck	Sw_Gothenburg	270.18	100
In_Madras	In_Paradip	654.28	150
In_Madras	SriLanka	491.53	150
In_Madras	BandaAceh	1107.35	150
In_JawaharlalNehru	In_Bombay	8.80	50
In_JawaharlalNehru	In_Mormugao	249.59	50
In_Calcutta	In_Paradip	192.52	50

From	To	Length (n.m.)	Penalty (n.m.)
In_Bombay	In_JawaharlalNehru	8.80	50
In_Bombay	Pa_Karachi	551.45	150
In_Paradip	In_Madras	654.28	150
In_Paradip	In_Calcutta	192.52	50
In_Paradip	BandaAceh	1126.90	150
In_Mormugao	In_JawaharlalNehru	249.59	50
In_Mormugao	In_NewMangalore	183.57	50
In_Mormugao	Oman	987.40	150
In_Mormugao	Socotra	1291.91	150
In_NewMangalore	In_Mormugao	183.57	50
In_NewMangalore	SriLanka	535.22	150
Io_TanjungPriok	SundaE	121.06	100
It_Genoa	It_Leghorn	90.32	50
It_Trieste	ItalyHeel	487.55	50
It_Taranto	ItalyHeel	107.06	50
It_Leghorn	Fr_Marseilles	248.40	50
It_Leghorn	It_Genoa	90.32	50
It_Leghorn	Messina	469.87	50
Ja_Nagoya	Ja_Yokohama	155.07	50
Ja_Nagoya	Ja_Kobe	102.68	50
Ja_Nagoya	Ph_Manila	1731.83	200
Ja_Nagoya	Darwin	3178.27	200
Ja_Chiba	Ja_Yokohama	28.65	50
Ja_Chiba	Ja_Tokyo	23.96	50
Ja_Yokohama	Ca_Vancouver	4708.13	200
Ja_Yokohama	Ja_Chiba	28.65	50
Ja_Yokohama	Ja_Nagoya	155.07	50

From	To	Length (n.m.)	Penalty (n.m.)
Ja_Yokohama	Us_LosAngeles	5489.76	200
Ja_Yokohama	Us_Valdez	3590.31	200
Ja_Kitakyushu	Ja_Kobe	252.83	50
Ja_Kitakyushu	Ko_Busan	136.05	100
Ja_Kobe	Ja_Nagoya	102.68	50
Ja_Kobe	Ja_Kitakyushu	252.83	50
Ja_Kobe	Ja_Osaka	17.42	50
Ja_Osaka	Ja_Kobe	17.42	50
Ja_Tokyo	Ja_Chiba	23.96	50
Ko_Busan	Ja_Kitakyushu	136.05	100
Ko_Busan	Ko_Ulsan	28.13	50
Ko_Busan	Jeju	168.88	100
Ko_Ulsan	Ko_Busan	28.13	50
Ko_Ulsan	Ko_Pohang	33.26	50
Ko_Inchon	Ch_Shanghai	523.34	150
Ko_Inchon	Ch_Yantai	288.30	100
Ko_Inchon	Jeju	249.11	100
Ko_Pohang	Ko_Ulsan	33.26	50
Ma_Kelang	Ma_TanjungPelepas	186.43	∞
Ma_Kelang	BandaAceh	496.79	150
Ma_TanjungPelepas	Ma_Kelang	186.43	∞
Ma_TanjungPelepas	Si_Singapore	17.23	∞
Ne_Rotterdam	Be_Antwerp	48.83	50
Ne_Rotterdam	Ne_Amsterdam	36.91	50
Ne_Amsterdam	Ne_Rotterdam	36.91	50
Ne_Amsterdam	Ge_Wilhelmshaven	153.08	50
No_Bergen	NorthSea	251.44	100

From	To	Length (n.m.)	Penalty (n.m.)
Pa_Karachi	Oman	380.60	150
Pa_Karachi	In_Bombay	551.45	150
Ph_Manila	Au_Hedland	2417.66	200
Ph_Manila	Ch_HongKong	701.91	150
Ph_Manila	Ch_Kaohsiung	581.54	150
Ph_Manila	Ja_Nagoya	1731.83	200
Ph_Manila	Si_Singapore	1486.75	150
Ph_Manila	Us_LosAngeles	7296.83	200
Ph_Manila	HornIsland	2252.84	200
Ph_Manila	LombokN	1570.66	200
Ph_Manila	PanamaW	10377.33	200
Ro_Constantza	Ur_Odessa	189.32	50
Ro_Constantza	BosphorusN	195.44	100
Ru_Novorossisk	Ur_Odessa	361.16	150
Ru_Novorossisk	BosphorusN	489.09	150
Ru_Primorsk	Ge_Lubeck	804.30	150
Ru_Primorsk	Ru_StPetersburg	55.86	50
Ru_StPetersburg	Ru_Primorsk	55.86	50
Sa_Jubail	Oman	763.95	150
Sa_Yanbu	Sa_Jeddah	189.51	50
Sa_Yanbu	SuezS	469.56	150
Sa_Jeddah	Sa_Yanbu	189.51	50
Sa_Jeddah	Aden	833.45	∞
Si_Singapore	Ch_HongKong	1609.96	200
Si_Singapore	Ma_TanjungPelepas	17.23	∞
Si_Singapore	Ph_Manila	1486.75	150
Si_Singapore	SundaE	517.76	150

From	To	Length (n.m.)	Penalty (n.m.)
So_RichardsBay	Au_Dampier	5234.11	200
So_RichardsBay	So_Durban	96.16	50
So_RichardsBay	Comoros	1269.86	150
So_RichardsBay	SundaW	4884.89	200
So_SaldanhaBay	So_Durban	801.29	50
So_SaldanhaBay	BrazilGroup	3592.26	200
So_SaldanhaBay	Natal	3839.20	200
So_SaldanhaBay	Dakar	4086.22	200
So_Durban	So_RichardsBay	96.16	50
So_Durban	So_SaldanhaBay	801.29	50
Sp_Algeciras	GibraltarW	282.62	∞
Sp_Algeciras	GibraltarE	303.88	∞
Sp_Valencia	Sp_Tarragona	142.40	50
Sp_Valencia	GibraltarE	187.16	50
Sp_Barcelona	Fr_Marseilles	209.96	50
Sp_Barcelona	Sp_Tarragona	51.50	50
Sp_Bilbao	Brest	401.45	150
Sp_Bilbao	Corunna	348.76	50
Sp_Tarragona	Sp_Valencia	142.40	50
Sp_Tarragona	Sp_Barcelona	51.50	50
Sp_Tarragona	Messina	791.52	150
Sw_Gothenburg	Ge_Lubeck	270.18	100
Sw_Gothenburg	NorthSea	252.70	100
Tu_Izmit	BosphorusS	55.16	50
Uk_Grimsby	Be_Antwerp	255.38	50
Uk_Grimsby	Ge_Wilhelmshaven	341.31	150
Uk_Grimsby	Uk_Tees	84.69	50

From	To	Length (n.m.)	Penalty (n.m.)
Uk_London	Fr_Dunkirk	113.04	100
Uk_Tees	Uk_Grimsby	84.69	50
Uk_Tees	Uk_Forth	117.48	50
Uk_Tees	NorthSea	295.60	100
Uk_Southampton	Fr_LeHavre	118.47	100
Uk_Southampton	Brest	229.88	100
Uk_Forth	Uk_Tees	117.48	50
Uk_MilfordHaven	Uk_Liverpool	152.99	50
Uk_MilfordHaven	Brest	201.52	100
Uk_Liverpool	Uk_MilfordHaven	152.99	50
Ur_Odessa	Ro_Constantza	189.32	50
Ur_Odessa	Ru_Novorossisk	361.16	150
Ur_Odessa	BosphorusN	360.85	150
Us_SouthLouisiana	USSouthGroup	750.94	50
Us_Houston	USSouthGroup	821.73	50
Us_NewYork	USEastGroup	249.70	50
Us_CorpusChristi	USSouthGroup	865.58	50
Us_LongBeach	Us_LosAngeles	17.83	50
Us_NewOrleans	USSouthGroup	605.90	50
Us_Beaumont	USSouthGroup	775.95	50
Us_Huntington	USEastGroup	651.60	50
Us_Mobile	USSouthGroup	596.86	50
Us_HamptonRoads	USEastGroup	341.50	50
Us_Plaquemines	USSouthGroup	550.00	50
Us_LosAngeles	Au_HayPoint	7164.14	200
Us_LosAngeles	Ca_Vancouver	1079.90	150
Us_LosAngeles	Ja_Yokohama	5489.76	200

From	To	Length (n.m.)	Penalty (n.m.)
Us_LosAngeles	Ph_Manila	7296.83	200
Us_LosAngeles	Us_LongBeach	17.83	50
Us_LosAngeles	PanamaW	3089.59	200
Us_LakeCharles	USSouthGroup	742.14	50
Us_TexasCity	USSouthGroup	783.86	50
Us_BatonRouge	USSouthGroup	671.46	50
Us_Tampa	USSouthGroup	400.93	50
Us_Baltimore	USEastGroup	339.66	50
Us_Paulsboro	USEastGroup	277.33	50
Us_Valdez	Ca_Vancouver	1217.69	150
Us_Valdez	Ja_Yokohama	3590.31	200
Us_Savannah	USEastGroup	744.52	50
Us_Pascagoula	USSouthGroup	587.19	50
Aden	Sa_Jeddah	833.45	∞
Aden	Socotra	623.62	150
BandaAceh	In_Madras	1107.35	150
BandaAceh	In_Paradip	1126.90	150
BandaAceh	Ma_Kelang	496.79	150
BandaAceh	SriLanka	1122.98	150
BandaAceh	SundaW	1110.74	150
BosphorusN	Ro_Constantza	195.44	100
BosphorusN	Ru_Novorossisk	489.09	150
BosphorusN	Ur_Odessa	360.85	150
BosphorusN	BosphorusS	44.26	∞
BosphorusS	Tu_Izmit	55.16	50
BosphorusS	BosphorusN	44.26	∞
BosphorusS	Myrina	212.02	100

From	To	Length (n.m.)	Penalty (n.m.)
BrazilGroup	Br_Tubarao	507.10	50
BrazilGroup	Br_Sepetiba	199.08	50
BrazilGroup	Br_Santos	305.12	50
BrazilGroup	Br_SaoSebastiao	255.11	50
BrazilGroup	Br_Paranagua	428.35	50
BrazilGroup	Br_AngradosReis	224.23	50
BrazilGroup	So_SaldanhaBay	3592.26	200
BrazilGroup	Natal	1459.56	50
BrazilGroup	Magellan	2564.64	200
Brest	Sp_Bilbao	401.45	150
Brest	Uk_Southampton	229.88	100
Brest	Uk_MilfordHaven	201.52	100
Brest	Corunna	403.43	150
Brest	USEastGroup	3227.52	200
Caribe	Br_Itaqui	3202.55	200
Caribe	GibraltarW	4066.71	200
Caribe	PanamaE	562.68	150
Caribe	USEastGroup	1649.23	200
Caribe	USSouthGroup	981.48	150
Comoros	So_RichardsBay	1269.86	150
Comoros	Socotra	2003.13	200
Comoros	SriLanka	2761.27	200
Corunna	Sp_Bilbao	348.76	50
Corunna	Brest	403.43	150
Corunna	GibraltarW	569.63	50
Crete	ItalyHeel	514.31	50
Crete	Messina	634.49	150

From	To	Length (n.m.)	Penalty (n.m.)
Crete	Myrina	306.84	150
Crete	SuezN	404.77	150
Dakar	So_SaldanhaBay	4086.22	200
Dakar	Natal	1728.21	200
Dakar	GibraltarW	1540.38	200
Dakar	USEastGroup	3531.81	200
Darwin	Au_Hedland	1073.89	150
Darwin	Ja_Nagoya	3178.27	200
Darwin	HornIsland	781.27	150
Darwin	LombokN	1044.52	150
Darwin	LombokS	1053.91	150
Darwin	SundaE	1623.76	200
GibraltarE	Sp_Algeciras	303.88	∞
GibraltarE	Sp_Valencia	187.16	50
GibraltarE	Messina	861.14	150
GibraltarW	Sp_Algeciras	282.62	∞
GibraltarW	Caribe	4066.71	200
GibraltarW	Corunna	569.63	50
GibraltarW	Dakar	1540.38	200
GibraltarW	USEastGroup	3253.77	200
GibraltarW	USSouthGroup	4477.24	200
HornIsland	Au_HayPoint	899.58	50
HornIsland	Ph_Manila	2252.84	200
HornIsland	Darwin	781.27	150
ItalyHeel	It_Trieste	487.55	50
ItalyHeel	It_Taranto	107.06	50
ItalyHeel	Messina	219.19	50

From	To	Length (n.m.)	Penalty (n.m.)
ItalyHeel	Crete	514.31	50
Jeju	Ch_Shanghai	348.39	150
Jeju	Ch_Yantai	381.23	150
Jeju	Ch_Lianyungang	423.69	150
Jeju	Ko_Busan	168.88	100
Jeju	Ko_Inchon	249.11	100
LombokN	Ph_Manila	1570.66	200
LombokN	Darwin	1044.52	150
LombokN	LombokS	126.38	∞
LombokN	SundaE	581.77	150
LombokS	Au_Hedland	779.93	150
LombokS	Darwin	1053.91	150
LombokS	LombokN	126.38	∞
LombokS	SundaW	814.90	150
Magellan	Au_Gladstone	6395.54	200
Magellan	BrazilGroup	2564.64	200
Magellan	PanamaW	4319.99	200
Messina	Fr_Marseilles	645.97	150
Messina	It_Leghorn	469.87	150
Messina	Sp_Tarragona	791.52	150
Messina	Crete	634.49	150
Messina	GibraltarE	861.14	150
Messina	ItalyHeel	219.19	50
Myrina	BosphorusS	212.02	100
Myrina	Crete	306.84	150
Natal	Br_Itaqui	2207.13	50
Natal	So_SaldanhaBay	3839.20	200

From	To	Length (n.m.)	Penalty (n.m.)
Natal	BrazilGroup	1459.56	50
Natal	Dakar	1728.21	200
NorthSea	Ge_Wilhelmshaven	245.97	100
NorthSea	No_Bergen	251.44	100
NorthSea	Sw_Gothenburg	252.70	100
NorthSea	Uk_Tees	295.60	100
Oman	In_Mormugao	987.40	150
Oman	Pa_Karachi	380.60	150
Oman	Sa_Jubail	763.95	150
Oman	Socotra	840.61	150
PanamaE	Caribe	562.68	150
PanamaE	PanamaW	459.36	∞
PanamaE	USSouthGroup	912.96	150
PanamaW	Au_HayPoint	8789.93	200
PanamaW	Ph_Manila	10377.33	200
PanamaW	Us_LosAngeles	3089.59	200
PanamaW	Magellan	4319.99	200
PanamaW	PanamaE	459.36	∞
Socotra	In_Mormugao	1291.91	150
Socotra	Aden	623.62	150
Socotra	Comoros	2003.13	200
Socotra	Oman	840.61	150
Socotra	SriLanka	1693.99	200
SriLanka	In_Madras	491.53	150
SriLanka	In_NewMangalore	535.22	150
SriLanka	BandaAceh	1122.98	150
SriLanka	Comoros	2761.27	200

From	To	Length (n.m.)	Penalty (n.m.)
SriLanka	Socotra	1693.99	200
SriLanka	SundaW	1975.67	200
SuezN	Eg_Alexandria	149.14	100
SuezN	Crete	404.77	150
SuezN	SuezS	199.31	∞
SuezS	Sa_Yanbu	469.56	150
SuezS	SuezN	199.31	∞
SundaE	Io_TanjungPriok	121.06	100
SundaE	Si_Singapore	517.76	150
SundaE	Darwin	1623.76	200
SundaE	LombokN	581.77	150
SundaE	SundaW	327.32	∞
SundaW	Au_Dampier	1263.72	150
SundaW	So_RichardsBay	4884.89	200
SundaW	BandaAceh	1110.74	150
SundaW	LombokS	814.90	150
SundaW	SriLanka	1975.67	200
SundaW	SundaE	327.32	∞
USEastGroup	Us_NewYork	249.70	50
USEastGroup	Us_Huntington	651.60	50
USEastGroup	Us_HamptonRoads	341.50	50
USEastGroup	Us_Baltimore	339.66	50
USEastGroup	Us_Paulsboro	277.33	50
USEastGroup	Us_Savannah	744.52	50
USEastGroup	Brest	3227.52	200
USEastGroup	Caribe	1649.23	200
USEastGroup	Dakar	3531.81	200

From	To	Length (n.m.)	Penalty (n.m.)
USEastGroup	GibraltarW	3253.77	200
USEastGroup	USSouthGroup	1387.95	150
USSouthGroup	Us_SouthLouisiana	750.94	50
USSouthGroup	Us_Houston	821.73	50
USSouthGroup	Us_CorpusChristi	865.58	50
USSouthGroup	Us_NewOrleans	605.90	50
USSouthGroup	Us_Beaumont	775.95	50
USSouthGroup	Us_Mobile	596.86	50
USSouthGroup	Us_Plaquemines	550.00	50
USSouthGroup	Us_LakeCharles	742.14	50
USSouthGroup	Us_TexasCity	783.86	50
USSouthGroup	Us_BatonRouge	671.46	50
USSouthGroup	Us_Tampa	400.93	50
USSouthGroup	Us_Pascagoula	587.19	50
USSouthGroup	Caribe	981.48	150
USSouthGroup	GibraltarW	4477.24	200
USSouthGroup	PanamaE	912.96	150
USSouthGroup	USEastGroup	1387.95	150

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